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ABSTRACT

This publication is an energy guide for teachers. It contains discussions and illustrations of five major topics: the sun's radiant energy, solar collection, solar cells, bioconversion (wood, grains, waste), and wind. Each section includes a listing of the concepts contained within and a brief discussion-explanation section. There is a short bibliography included. (MA)

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ENVIRONMENTAL ENERGY EDUCATION PROJECT

science packets

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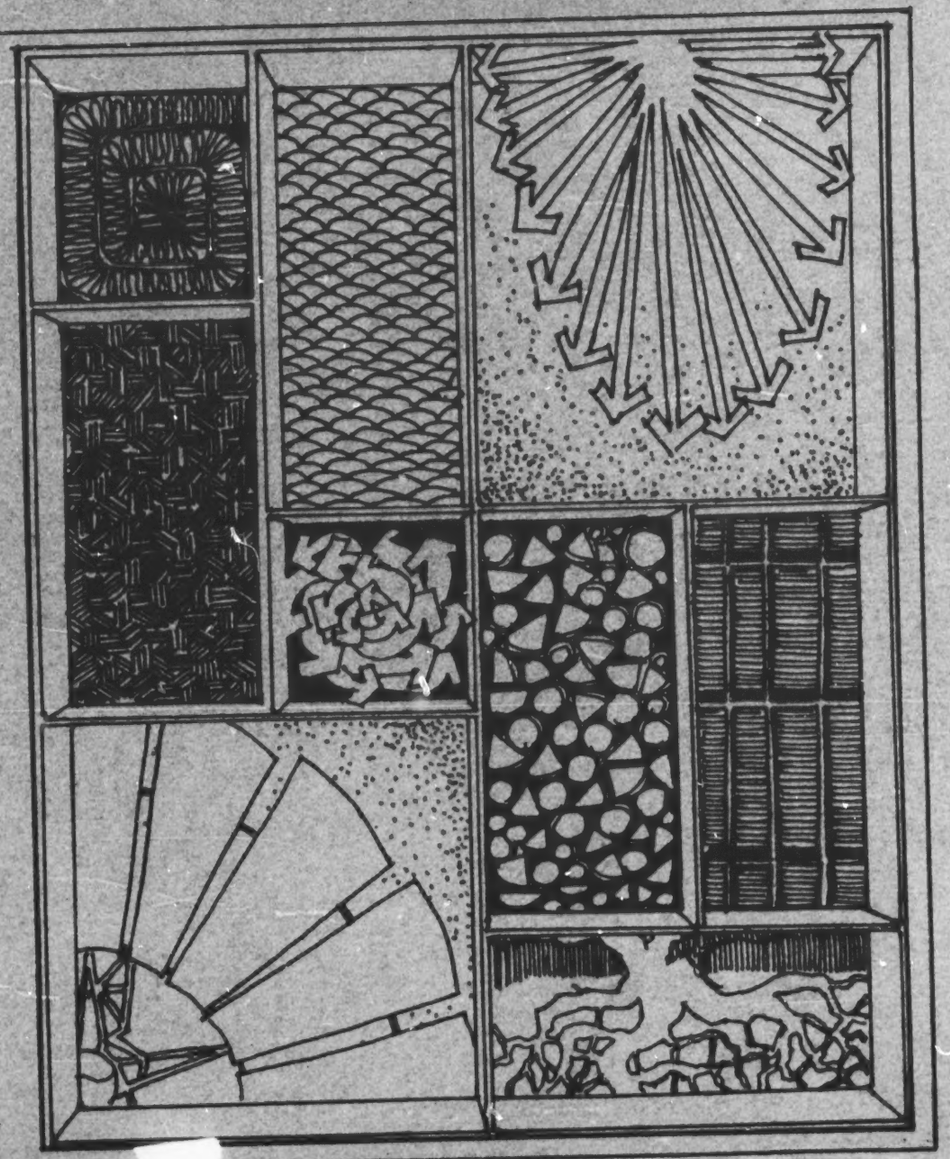

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Jonathan Gorham
EEEP Director

September 1977
Falmouth, Maine

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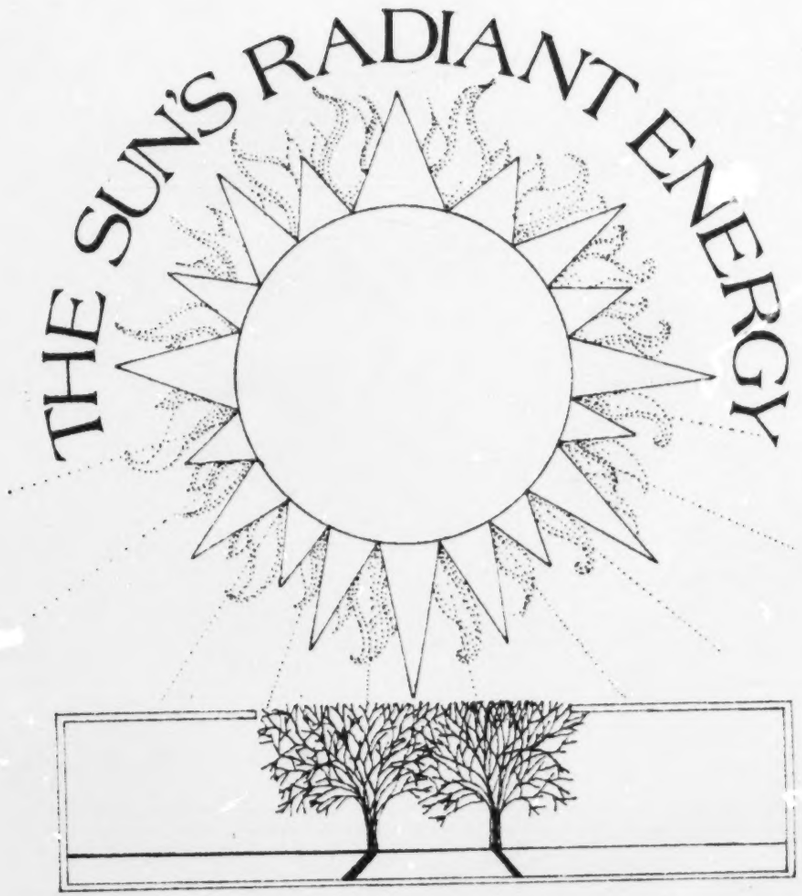


The Sun's Radiant Energy

Concepts:

Quantification of Solar Radiation
Earth-Sun Relationships
Direct and Diffuse Radiation
Intensity of Light on a Surface
Altitude Angle
Azimuth Angle

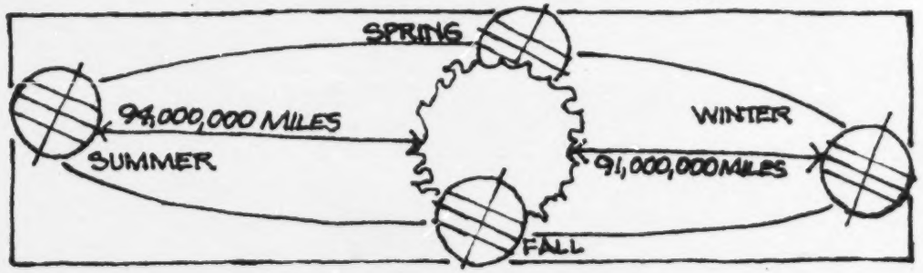
Situated roughly 93 million miles from earth, the sun radiates unfathomable amounts of energy. Several key factors determine the amount and intensity of solar energy that reaches the earth's surface in any given place. These factors include the distance the sun must travel through the atmosphere, the quality of the atmosphere and the angle of the sun's rays relative to the intercepting surface. This packet discusses these factors and the usability of solar radiation.

> While the sun is shining, the energy equivalent of a gallon of gasoline (36 kWh) falls on an area the size of a tennis court about every ten minutes.
>
> The world's largest steam powered electric plant in Kingston, Tennessee supplies 1.5 X 10^6 kW. We would need 170 million such plants to produce the amount of solar energy that falls on the earth in one year.
>
> The solar energy striking a football field in Miami during the course of one hour, at about noon, during the middle of June, is equal to the energy contained in about 360 kilos (800 lbs.) of coal.

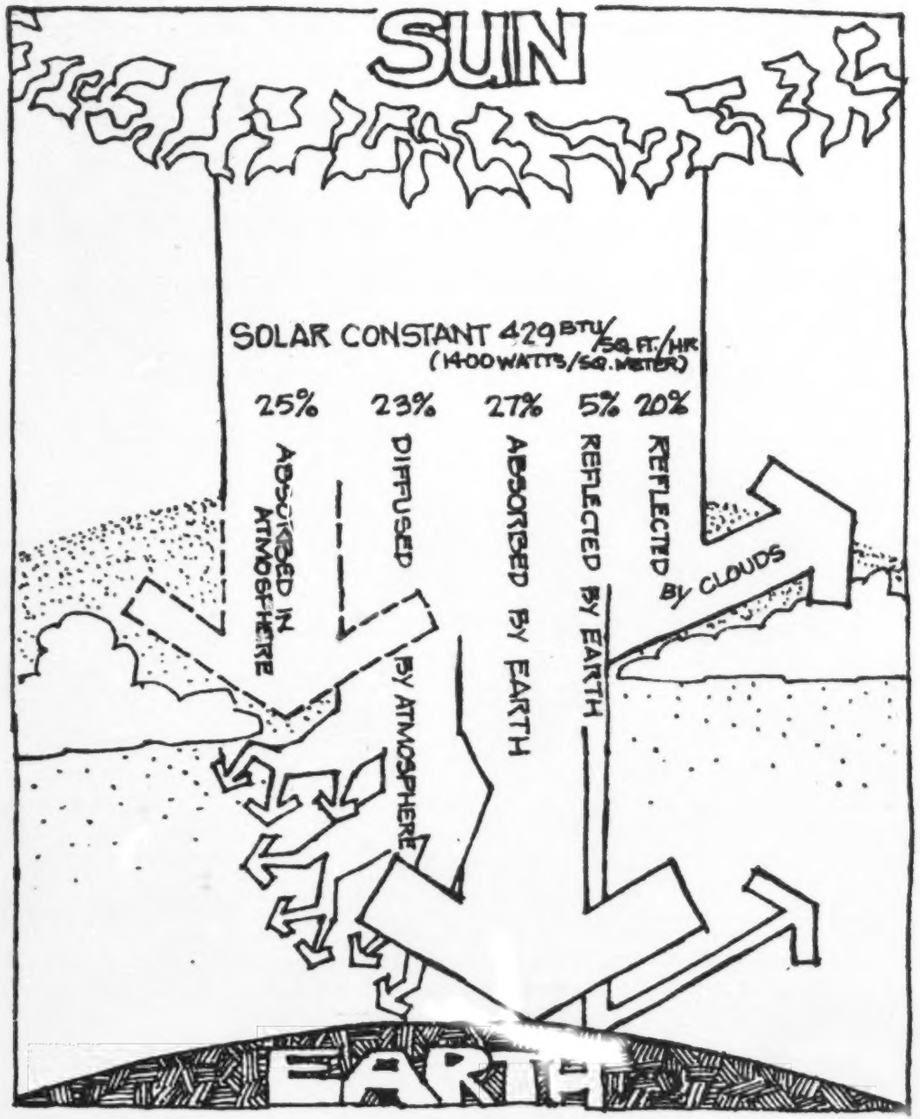
If there is this abundance of solar radiation, how much of it is usable, and what factors determine this? Let us first discuss the path of radiant energy from sun to earth.

Explanation:

1. 4.4 billion kilograms (4.4 million tons) of matter are charged with energy each second on the sun.
2. 3.8 x 10^{26} watts are radiated in all directions (1.3 X 10^{27} btu/hour).
3. Energy travels through space from the sun to the earth. The distance this energy must travel varies with the time of year due to the elliptical orbit of the earth. The sun



   is actually closer to the earth at the winter solstice, December 21, than at the summer solstice, June 21.
4. The intensity of radiant energy is a function of distance from the source. The sun's radiation is more intense on Mercury than on Venus; Venus gets more sunlight than earth. As distance increases, intensity decreases according to the formula $I=1/d^2$ (intensity=light/distance^2). In June we receive 413.1 btu/ft^2/hour, contrasted to December when we receive 441.0 btu/ft^2/hour. 6% more solar energy arrives at the earth's outer atmosphere during the winter, but the increased atmospheric distance through which the rays must travel, dissipates the energy, making them less useful.
5. The earth receives only a small part of the sun's total energy output: 1/200 millionth. Still this is a very large quantity - 1.73 X 10^{17} watts (5.90 X 10^{17} btu/hour).



6. The intensity of radiation reaching the upper surface of the atmosphere is taken as the solar constant. It may vary ± 2% due to variations in the sun's energy output and ± 3.5% due to changes in distance between the earth and sun. The solar constant is 429.2 btu/ft^2/hour.

Quality of Atmosphere

The amount of solar radiation that reaches the earth's surface is extremely variable; it ranges from 0-50% of the energy available at the earth's outer atmosphere. The quality of the atmosphere is a determining factor in the amount of insolation (incident solar radiation) reaching the earth's surface. Clouds, water vapor and carbon dioxide in the atmosphere will absorb and emit infrared radiation. The presence of these factors during daylight hours will reduce the amount of insolation during the day. At nighttime it will reduce the amount of heat that is lost to the atmosphere by providing a cover. The amount of usable energy is restricted still further by the efficiency of our means of conversion.

Explanation:

1. The radiation that reaches the earth's atmosphere is one of two forms:
   a. direct - parallel rays undeflected by the earth's atmosphere;
   b. diffuse - multi-directional radiation that is reflected from clouds, atmospheric dust and moisture particles.
2. Specific factors reducing solar radiation include:
   a. clouds - on a cloudy day up to 80% more energy is reflected and absorbed;
   b. carbon dioxide - produced as a by-product of respiration, CO_2 strongly absorbs the radiation in certain bands of infrared light;
   c. air pollution - a further reduction of 2% will be caused by pollutants: smoke, dust, chemical particles;
   d. geographic location - location near ocean areas, snow covered areas, desert areas will also affect the amount of solar energy that is absorbed and reflected.

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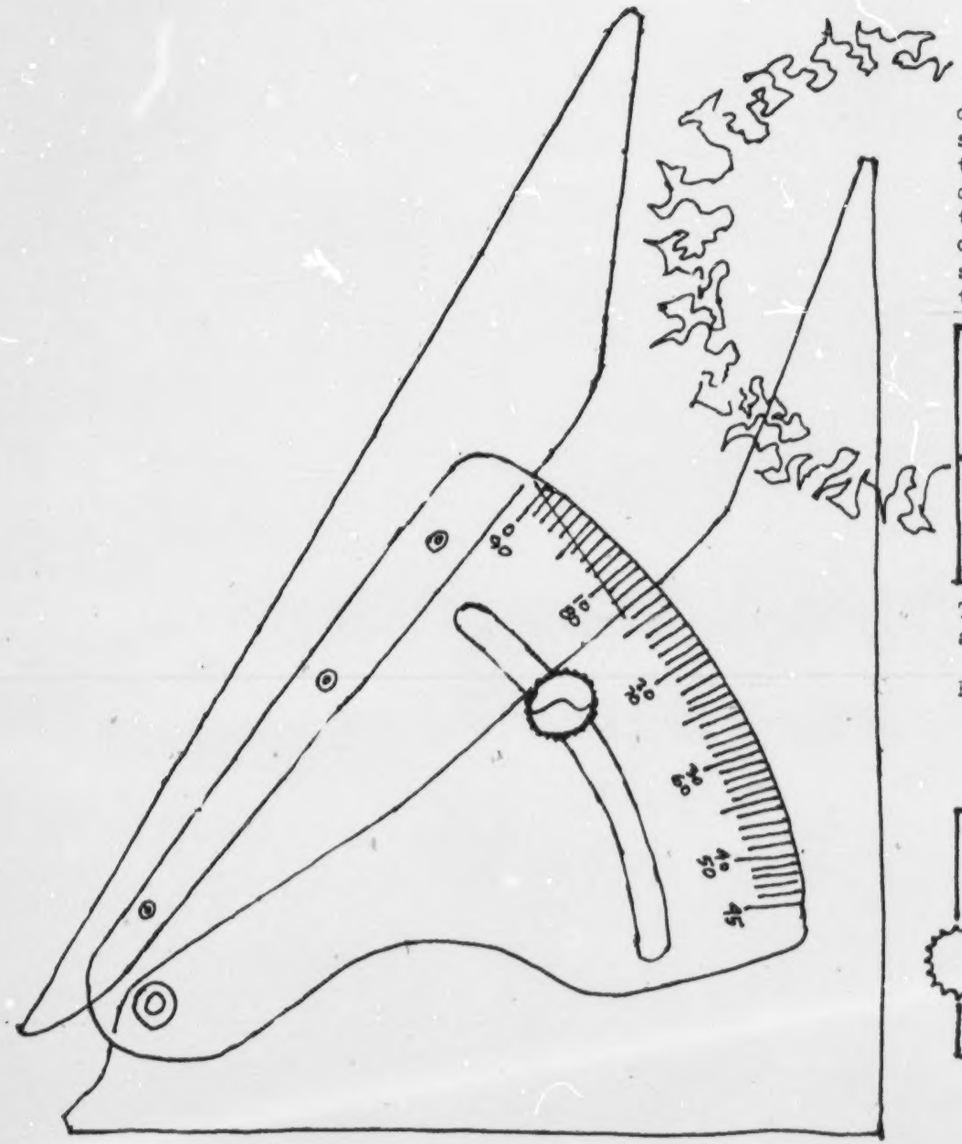
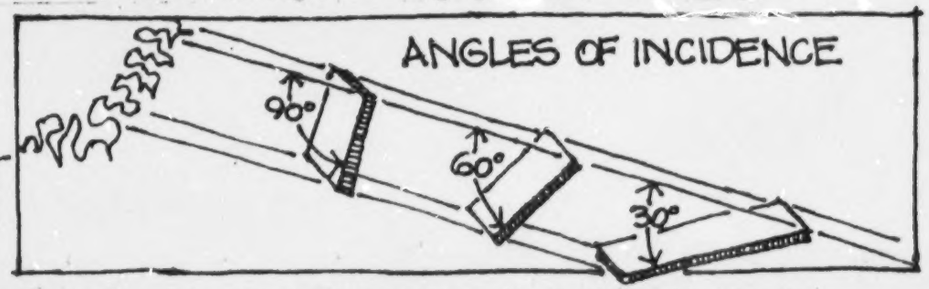


Solar Angles

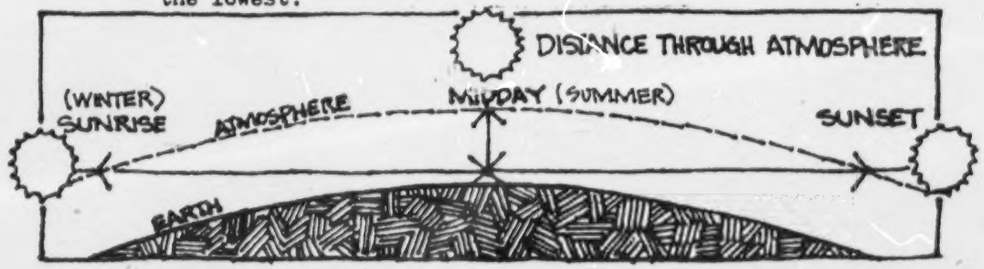
The angle of the sun's rays relative to the earth's surface determines the intensity of the rays. The energy received from the sun is most intense when the rays strike the earth most vertically, thereby traversing the minimum distance. This occurs around midday. The angle of incidence, (the angle between the direction of the sun and the perpendicular to the surface on which it is falling) determines the intensity of the sun's rays. The intensity on a surface further decreases as the incident angle increases because the same amount of light is being spread out over a larger area.



The angle of incidence at any given site is determined by the altitude and azimuth angles of the sun.

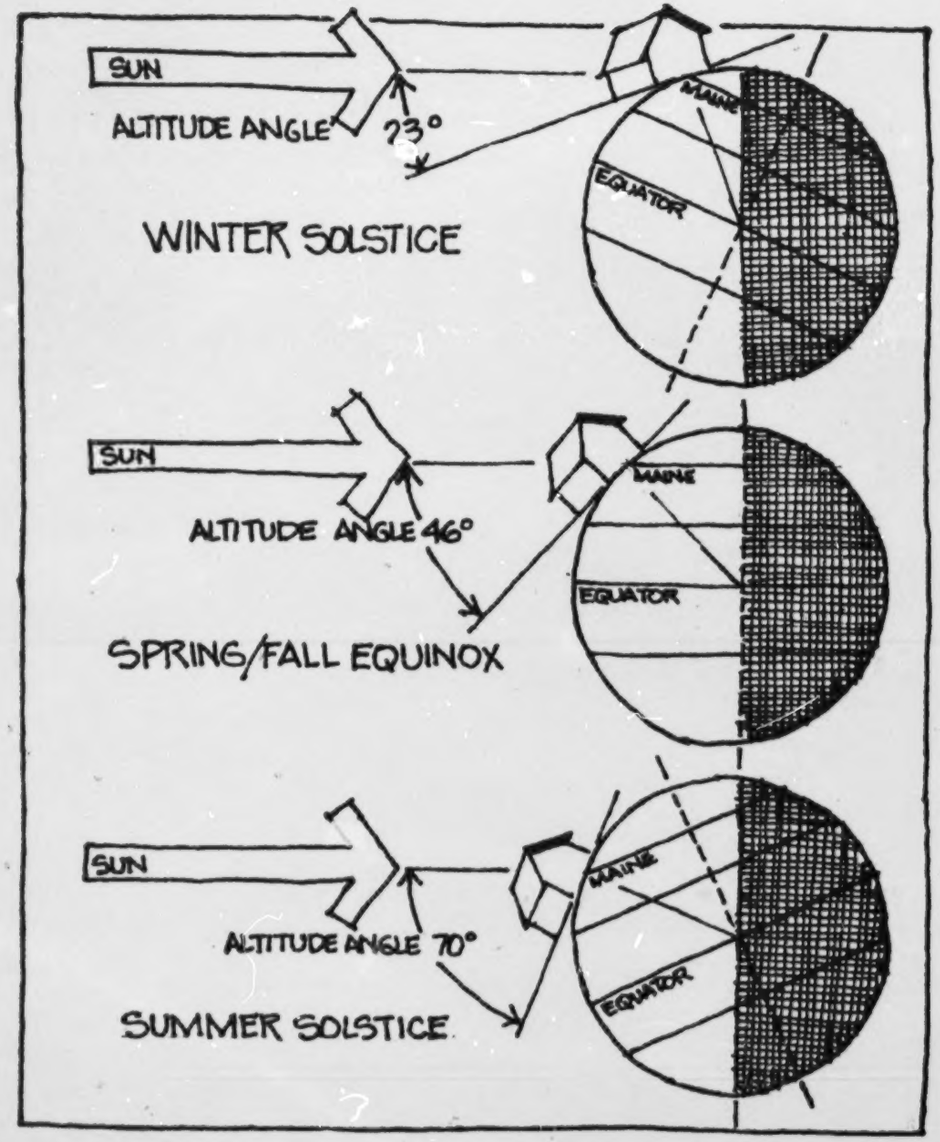
Explanation:

1. If the sun is most verticle at midday, then it follows that the angle of incidence at sunrise and sunset are the lowest.



2. The light at sunrise and sunset (and all the time on either side of midday) must travel a greater

3.



distance through the atmosphere than at midday. The further light must travel through the atmosphere, the greater the chance that the energy will be reflected or absorbed by molecules in the air.

3. Altitude angle is the angle of the sun above the horizon.

   In Maine, which ranges from 43° - 47° north latitude, we experience the sun (assume 44° N latitude to be average) at a maximum angle of 70° on June 21st and a minimum angle of 22° on December 21st. In Maine, we never receive direct, overhead solar radiation.

4. Azimuth angle refers to the angle of the sun relative to the north-south line; it is the only incident angle that can be altered. This can be done by changing the site orientation of a building or a collector.

   The angle formed by an object (say a flat plate collector) and direct south on the compass is the azimuth angle. A collector facing due south has an azimuth angle of 0°. Generally speaking, a direct southern exposure will provide maximum insolation.

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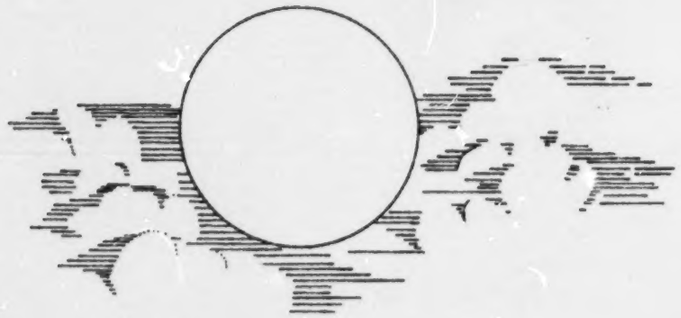


solar collection

Solar Collection

Concepts:

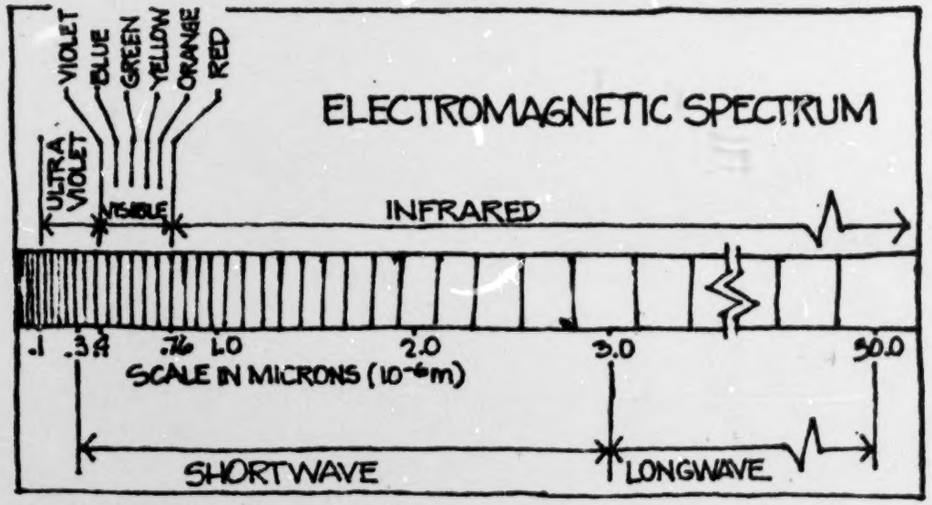
- Wavelength Conversion
- De Broglie's Equation
- Kinetic Energy of Light
- The Earth as a Solar Collector
- Passive Solar Collection
  - a. Thermal Mass
  - b. Specific Heat
  - c. Latent Heat
- Active Collectors
  - a. Flat Plate Collectors
  - b. Concentrating Collectors

The sun provides both the heat and light that our planet needs. In essence, the earth is a gigantic solar collector. The utilization of this energy can be maximized by both passive and active collector systems. This packet discusses the process of changing light energy to heat. In addition, it explores some of the principles of the developing technology for the collection and transport of this heat.

Wavelength Conversion

Direct solar radiation arrives in the earth's atmosphere in varying wavelengths. The shorter the wavelength, the higher the concentration of energy, i.e., the heat available from shortwave radiation is greater than that available from longwave radiation. In addition, the shortwave radiation is more prone to losing this energy. Longwave radiation is able to sustain its lower energy for a longer period of time. This is the energy we are familiar with as heat energy. In the process of wavelength conversion, shortwave radiation can be converted to longwave radiation. This conversion occurs as the radiation strikes the particles of a surface, is absorbed and is re-radiated as longwave radiation.

Some of the waves in the electromagnetic spectrum are those of visible light. Each color in the spectrum has a different wavelength. When the light particles strike a surface, it is either absorbed or reflected. Different colored surfaces absorb



different wavelengths of light, i. e. a green absorber will reflect green light and all other wavelengths will be absorbed. A white surface will reflect all light and a black surface will absorb all wavelengths. Therefore, a black surface is optimal for wavelength conversion.

How does this conversion from shortwave to longwave radiation occur? Let us trace the path of a single photon of light as it strikes the earth's surface.

Explanation:

1. A light photon arrives at the earth's surface with energy inversely proportional to it's wavelength.

De Broglie's Equation

$$E = h \times \frac{1}{\lambda}$$

E = energy
h = Planck's constant = 6.626×10^{-34} J/ second^2
J = Joules
λ = lambda = wavelength in meters

1.

2. Energy of the photon is transferred to the atoms of the absorbing surface by means of direct collision. (Law of Conservation of Energy) It should be noted that photons of light have energy that can be used directly without being converted to heat, as illustrated by a radiometer. The force of the light pushes the blades. The force of this energy is very small as quantified by De Broglie's Equation;

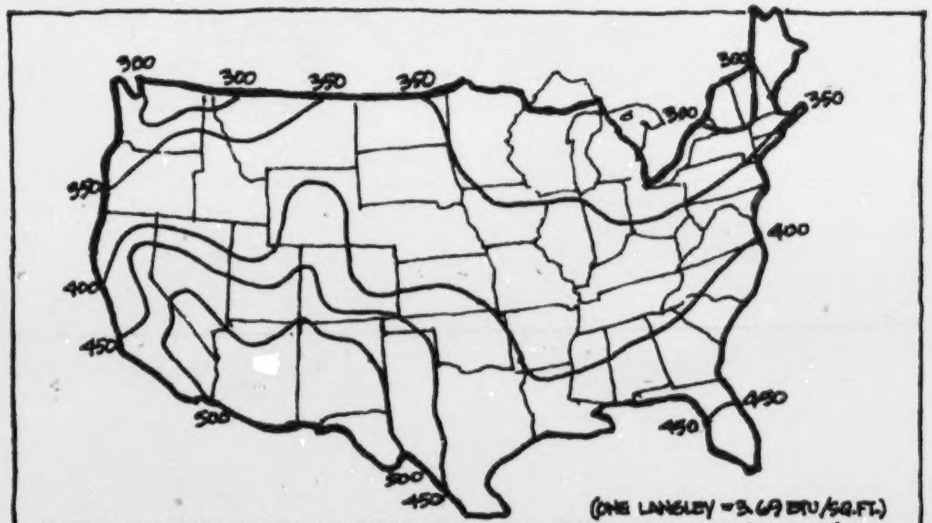
$$E = h \times \frac{1}{\lambda}$$

3. Upon collision with particles of a particular surface, the kinetic energies of the particles of the absorbing surface are increased. This energy takes the form of molecular vibration and displacement of electrons to higher atomic levels.
4. The energy from a single photon of light (short wave radiation) has been dispersed to the multiple particles of the absorbing surface. The energy is absorbed and re-emitted as lower energy, longer wavelength radiation. It is thus re-emitted at a lower temperature, but will emit radiation for a longer time.

The mole equivalent energy of ultraviolet radiation of 225 nanometers (10^{-9}m) is 128 kcal/mole, blue light of 450 nanometers is 32 kcal/mole.

Solar Collection

The sun striking the earth's surface is the energy supply for our largest heat collector; the earth itself. Of the available energy from the sun, only about one half actually penetrates to the earth's surface. The other half is either absorbed within the atmosphere itself by oxygen, ozone, water droplets and carbon dioxide, or it is scattered by air molecules, water vapor, aerosols, dust and other particles. The heat that actually reaches the earth's surface is either absorbed by the soil, rock mass, or bodies of water and re-radiated to the surrounding air, or immediately reflected back into the atmosphere. During non-light hours, clouds will help to retain the heat absorbed by the earth during the daytime. During sunlight hours they will prevent a varying percentage of the sun's energy from reaching the earth's surface. The basic principles of absorptivity and emissivity (the relative powers of a surface to absorb and re-emit radiation) as exhibited by the earth, apply to all forms of solar collection. Although solar collectors may vary greatly in their components and complexity, they all achieve three basic objectives: to capture the sun's radiant energy, to store, and to distribute its heat. The choice of system components and the way in which they are combined, determine the type of system.



AVERAGE INSOLATION ON A HORIZONTAL SURFACE IN LANGLEYS/DAY

Passive Solar

Passive solar systems are the most basic solar collection systems. The building itself is designed to be the collector. Heat is not actively transported to a storage system. The passive solar building is designed to admit maximum solar insolation, to minimize heat loss through all other surfaces, and to retain heat for use during non-light hours. A well designed passive solar building will promote these concepts and provide a comfortable environment.

The following discussion of passive systems explores some of the key concepts of solar heating.

1. Site orientation - South facing windows are integral to all solar designs. They are used to admit the sun's radiant energy, to heat up both interior objects and surfaces, and the air. This heat can be absorbed by thermal mass (e.g. furniture, floors, walls, etc.) of the building. This passive mode is usually not a long term storage system. It will not provide heat for extended periods of time in the absence of sunlight.
   The greenhouse is an example of using south facing windows for maximum solar gain. A greenhouse attached to a house has an increased surface area for the capturing of solar radiation. It can be completely shut off during non-light hours or insulated to retard heat loss. Using insulated shutters or curtains will again minimize heat loss.

2. Thermal Mass - The use of thermal mass as heat storage involves raising the temperature of a chemically inert substance such as rock, masonry or water by the absorption of heat through the surface. There are three principles basic to understanding how thermal mass functions as a heat storage area.
   a. Specific Heat - The amount of heat required to raise a certain mass of material by one degree F.
   b. Latent Heat - The amount of heat required to produce a phase change in a certain mass.
   c. Phase Change -

All materials exist in three phases; solid, liquid and gas. The most common material for which all three phases are familiar is water; ice, water, and water vapor. Heat is the kinetic energy (energy of motion) of a substance. The more heat we add, the more the atoms of molecules move, the less dense the material becomes. Within one phase, addition of heat raises the temperature of a substance; a drop in temperature implies that heat is given off. At a specific combination of temperature and pressure, radical structural changes take place in the material (the phase change). Characteristacally, much more heat must be added to effect a phase change than to simply raise the temperature by one degree. Also, rather remarkably, during a phase change, the temperature remains absolutely constant until the entire mass has undergone phase change. There are also a number of chemical phase changes that can occur.

Explanation:

Using Glauber's Salt:

Glauber's Salt is in a solid state in the temperature range of 24° - 49° C (75° - 120°F). With the addition of heat from the solar collector, the chemical changes to a liquid state. The heat that is absorbed by the chemical for this phase change is latent heat. When circulated through the transport system the temperature of the chemical is lowered and crystallization takes place creating an exothermic reaction.

3.

Table #1 lists specific heats and latent heats for several common materials.

Table #1

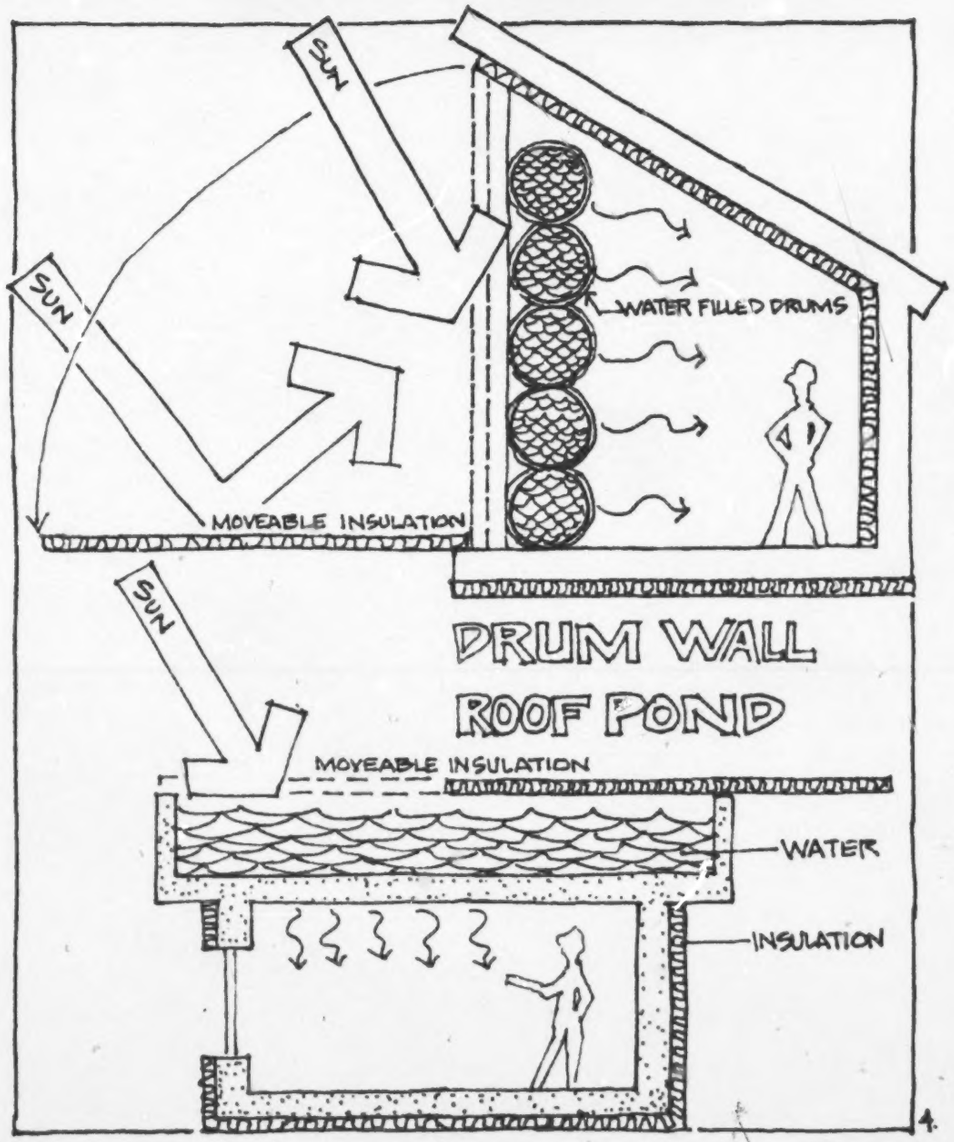
SUBSTANCE	DENSITY LB/CU. FT.	SPECIFIC HEAT BTU/LB. °F.	LATENT HEAT BTU/LB.
Water	62.4	1.0	144 @ 32°F.
Stone	180	0.21	
Iron	490	0.12	
Paraffin	55	0.70	65 @ 100°F.
Glauber's Salt ($NaSO_4$. 10 H_2O)	90	0.40	104 @ 90°F.
Fused Salt ($NaNO_3$)	140	0.38	80 @ 510°F.

Of the materials listed in Table #1, the first two are used almost exclusively due to cost. Of the other possible materials, Glauber's Salt is the most attractive, since it is not extremely expensive. However, technical problems have arisen (e.g.material stratification and loss of ability to store heat) which makes the use of Glauber's Salt questionable.

Following is a discussion of two basic storage systems utilizing thermal mass. Specific examples are included for each type of system.

Water - The designer, Harold Hay, has constructed several "roof pond" systems. The roof consists of (from the bottom up) an uninsulated ceiling (usually metal supported by steel beams), a wall-to-wall layer of "water bed", and finally, giant insulated motor-operated insulation panels. On a sunny day, the panels retract, exposing the water beds to the sun. At sunset, the panels close, preventing the upward heat loss from the water beds. Insulation on the underside is neglibile so that the heat flows downward into the living space. In the summer, the operation is reversed. Opening the panels at night allows the bags to cool by radiation to the cold night sky. During the day, the panels are closed and the bags absorb excessive living space heat.

An alternative system is the "drum wall". The designer, Steve Baer, erected a rack of water-filled 55 gallon drums in front of a glass south wall. During the day the sun striking the



black ends of the drums warms the contained water. At night, giant insulating shutters cover the windows, reducing heat loss.

Masonry - The same passive-solar tricks can be played using masonry instead of water as a storage medium. The simplest system is not far removed from ordinary construction techniques. A concrete slab insulated from below serves as the floor. The south-facing windows or greenhouse are placed to maximize the direct radiation on the slab. Window covers at night again reduce night time heat losses. One drawback of this system is a cold, hard, unattractive floor surface. Sometimes the slab is covered with bricks, tile, or slate.

A more effective but less conventional technique is the Trombe wall. It consists of a concrete wall about 12" thick, erected just behind large south-facing windows. The heat balance between the spaces in front and behind the concrete wall is controlled to some extent by controllable louvers at the base and top of the wall. Again, the windows are insulated at night. The drawback of the Trombe wall is that it blocks the direct sunlight and view from the living space behind.

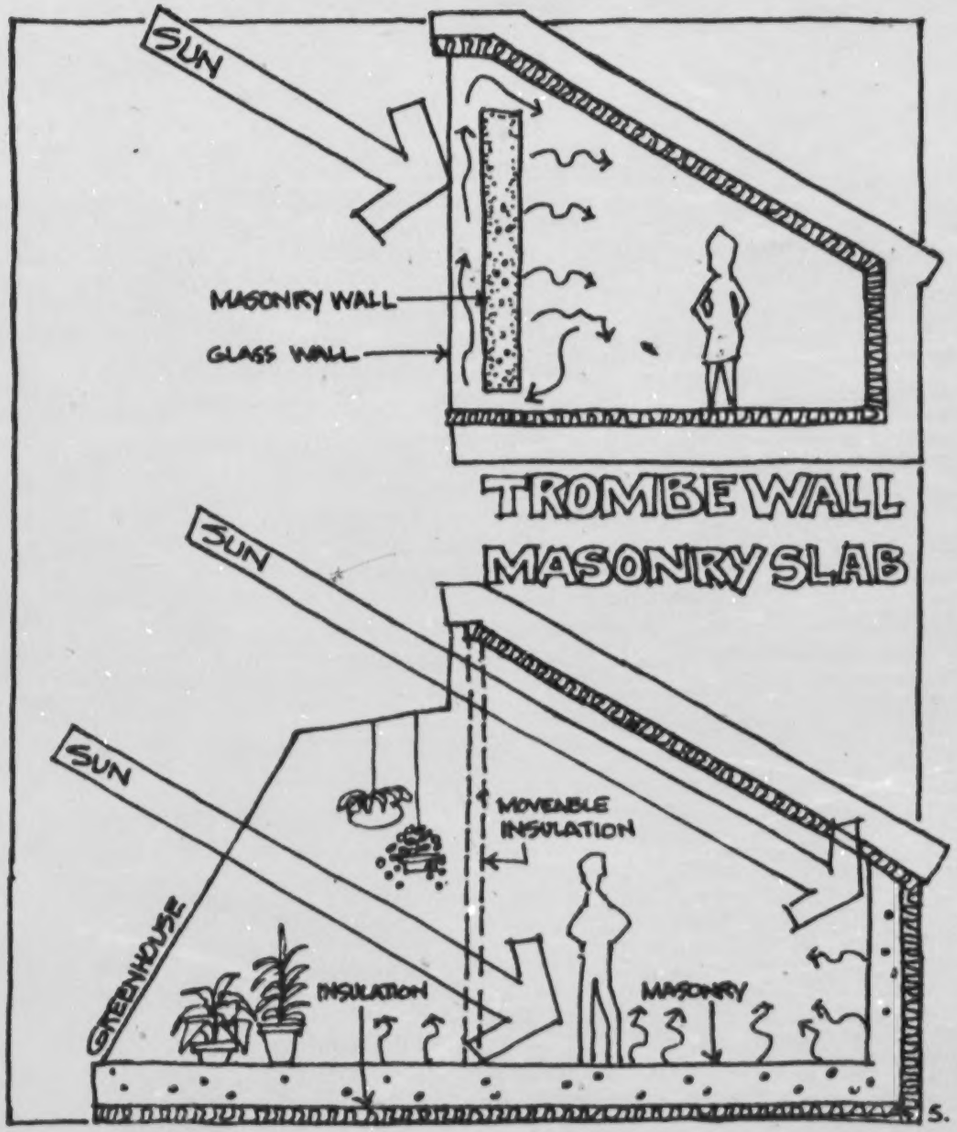
Both of the water systems are more effective than the masonry systems because the convecting water allows the heat to be taken up more rapidly. None of the passive systems are as controllable or predictable as the active systems, but they compensate by costing little more than conventional construction.

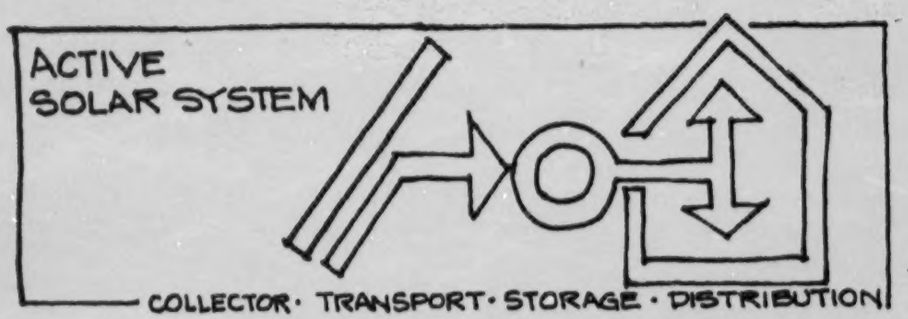
Advantages:

In passive solar buildings emphasis is placed on site orientation, design and construction materials. Because the use of special equipment is avoided, initial investment is low, as are maintenance costs. The passive solar home can be constructed by builder's without special skills and equipment making it accessible to virtually all home builders.

Disadvantages:

The primary disadvantage with a passive solar building is the lack of precise control of room temperatures. A long period without sun can rob the thermal mass of its stored heat so that a comfortable interior temperature is difficult to maintain. This time lag can be overcome with the addition of fans and by isolating and insulating the thermal mass. The system is thus taking on active components.



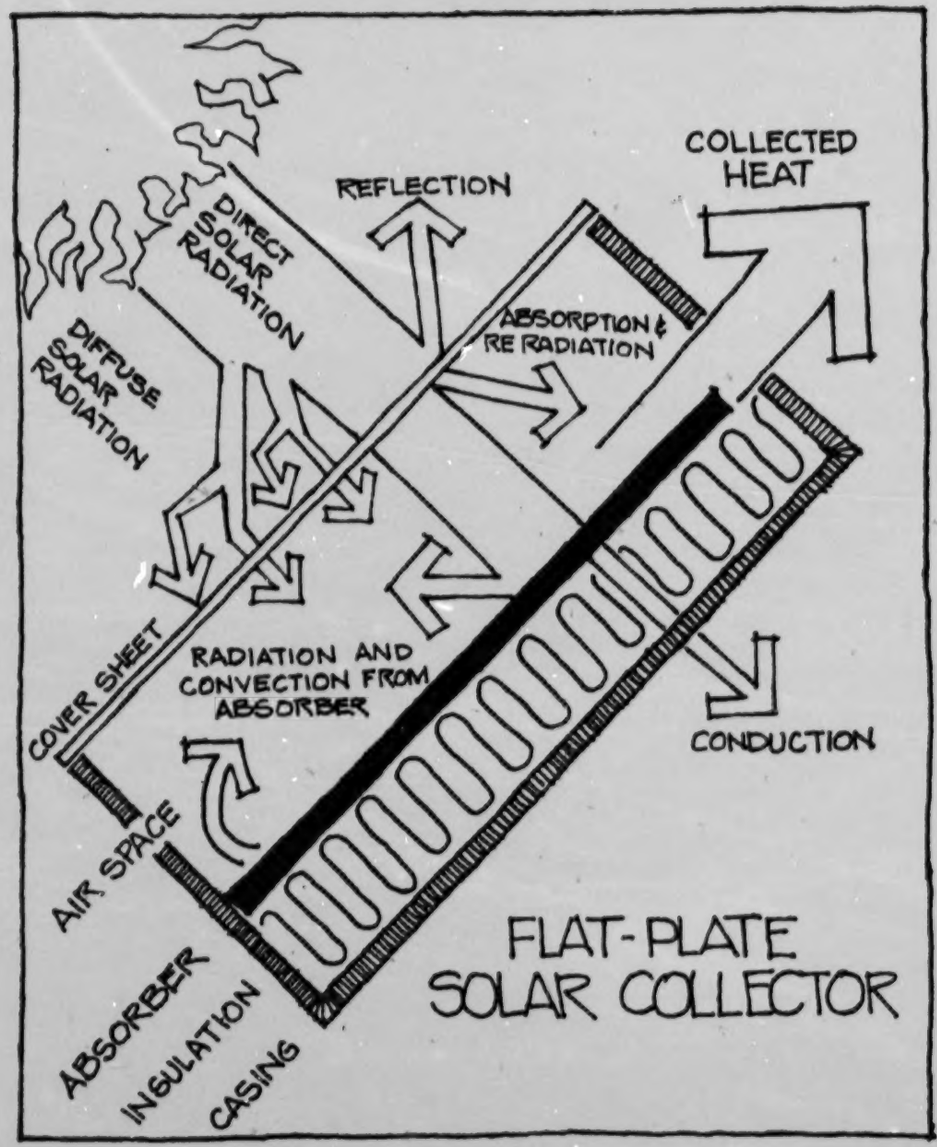


Active Solar Systems

Active solar systems collect the sun's radiant energy and transport it to a storage system where it is stored for use in space and /or water heating. This section discusses flat plate and concentrating collection systems, air and fluid transport systems, and rock and water storage systems.

Flat Plate Collectors - Flat plate collectors are the most widely used non-focusing collector. The collection and storage principles are similar to those of the earth's atmosphere. The three major components are: the absorber, insulating material and the cover sheet. The performance of any collector is largely a function of the amount of incident radiation, the absorptivity and emissivity (the relative powers of a surface to absorb and re-emit radiation) of the surface of the collector plate, the amount and type of insulation of the collector and the transmissivity and emissivity of the cover sheets.

Flat Plate Components - 1) A glazing, consisting of a substance which will allow light to pass through, yet prevent the reradiated long wave heat radiation from escaping, 2) a fluid or air duct grid mounted at least 1" below the glazing which captures and transports the heat to either the living space or the storage area, 3) an absorptive plate, generally black in color, which will absorb the radiation and conduct or convect it to the transporting medium (fluid or air), and 4) a casing which shields, protects and insulates the components from the outside weather.



Let's examine 3 common types of flat plate collector systems:

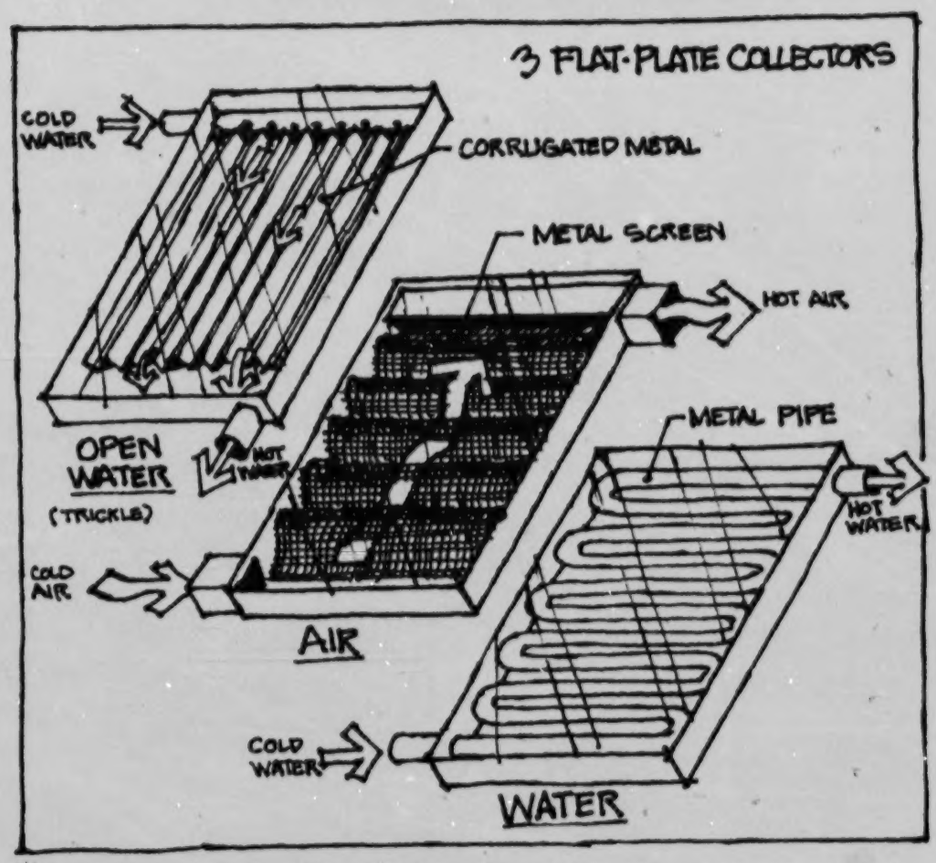
Air - The Maine Audubon building uses air type collectors. The air is trapped in the collector, converted to heat energy (wavelength conversion), the heat is absorbed by the absorptive plate and transported to the storage system.

Trickle type - Used in the Thomason house in Washington, D. C. This collector uses black corrugated metal roofing panels with a water flow system from top to bottom. The water is fed from a supply gutter at the top of the system, trickles down the troughs of the absorptive panel where it is heated, and is collected at the bottom where it is transported to storage.

Liquid - Liquid collectors are the most common type of collector now available. Water or a water/antifreeze solution is used as the heat transer medium. The fluid is piped, under pressure or by thermosyphon, through tubing that is either attached, or integral, to the absorber plate. The fluid is collected at the other end of the absorber plate and piped to the storage area.

Storage - Water and rock are both used as storage mediums due to their sensible heat capacity (the ability of a material to hold heat without a change in it's physical state, due to its composition and density). In general, rock storage is used with air type collectors and water storage is used with liquid type collectors, although there are systems which combine both types.

Rock - Generally used with air systems, the air is ducted through the rock where it circulates, gives up its heat to the rocks and is recycled to the collector. In rock storage, it is important to have rocks of a uniform dimension 1-5" in diameter for increased surface area and relatively shallow bed to minimize resistance of the circulating air. The heated air can then be ducted to the living space.



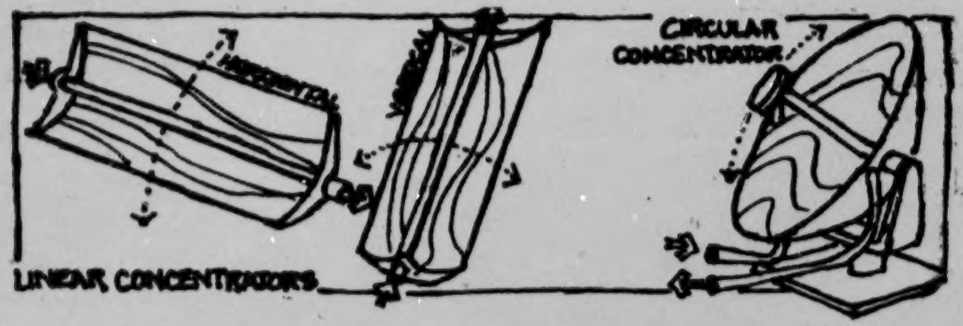
Water - As discussed earlier, water has a very high specific heat which means it can hold a large amount of heat relative to it's volume. The transport medium is pumped through the water storage and can be retained for later use, or circulated for domestic hot water or space heating.

Distribution - Heat in storage can be used by a heat pump, an absorptive air conditioner or by forced circulation through conventional heating systems utilizing fluid or air distribution.

7.

Concentrating Collectors

Concentrating or focusing collectors, collect the sun's energy and intensify it. They consist of a curved, mirror-like surface; some parabolic in shape, others through-like. The collector receives the sun's rays on this surface and reflects it to a small absorbing surface where it heats the storage medium. Concentrating collectors function at a maximum efficiency only when direct radiation is being received. For this reason they are best suited to areas with very clear skies.



Linear Concentrating Collector - A linear through-like collector is curved in one direction. This collector focuses radiation on a pipe or tube absorber. Fluid is circulated through the tube, pick's up the absorbed heat and transports it to a storage area.

Circular Concentrating Collector - A concave, reflective surface, often parabolic in shape, that is used to focus solar radiation on a point target area. The absorber is located at the focal point and collects heat. It is transported by a fluid to the storage area. The circular concentrating collector is most commonly designed to track the sun in order to take advantage of the most direct solar radiation.

Advantages - Solar collectors use the most plentiful and renewable resource of all - sunlight. The energy is free and non-polluting. Solar collectors can be designed as an integral part of the building structure, thereby avoiding costly retrofit. The design of low technology and collectors made of inexpensive or recycled materials is a challenge and available to all back yard tinkerers. With the continuing depletion of our planet's fossil fuel supply and the continuing escalation of electricity prices, solar energy becomes more and more feasible.

Disadvantages - The primary disadvantage of using solar collectors lies in the high initial capital investment. (A solar collecting system for home needs can cost an additional $2,000 to $5,000 or more, depending upon the elaborateness of the system.) Because of the newness of the industry, there does not exist a long track record of collector performances. Few collectors are guaranteed for any extended period of time, making it difficult to get bank loans which amortize the cost over the necessary twenty year period. There also exists a consumer fear that new technological developments will soon render any system they buy "obsolete".

Outlook - The outlook for increased use of solar collection units is extremely favorable. With a national goal of 2 1/2 million solar heated buildings by 1985, there is a demand for stepped-up development and production of solar collection equipment. As our supply of non-renewable resources continues to shrink, capturing solar energy to heat our buildings and hot water becomes both more desirable and imperative. In recognition, federal tax incentives, in the form of rebates or deductions for solar heating equipment are being seriously considered, and in several states such incentives are now being written into law.

Though long overdue, such a shift of emphasis towards alternatives to coal, oil and nuclear power, is certainly heartening.

B.

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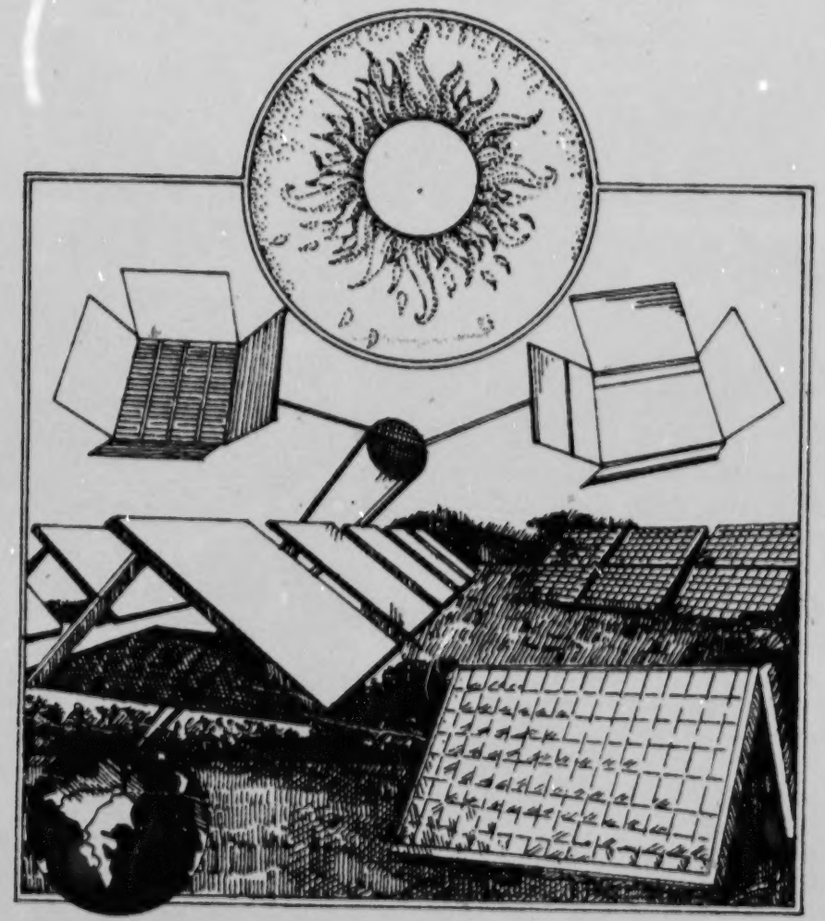
SOLAR CELLS



Solar Cells

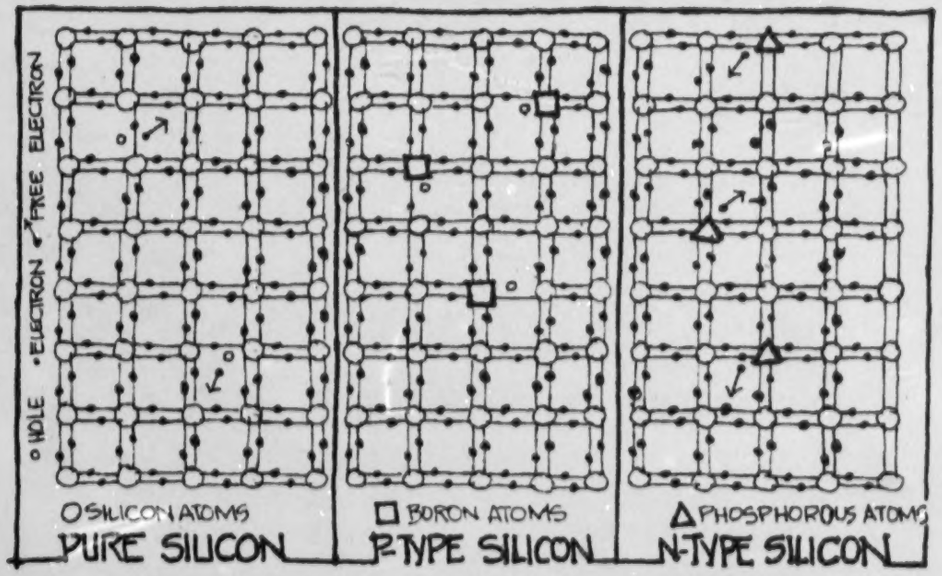
Concepts:
- Atomic Structure
- Valence
- Electron Flow
- Photo Electric Effect
- "Doping of Electrons"

Solar cells, a form of photovoltaic cells, were developed in the 1950's. To date, their most well known use is in spacecraft where they provide the electricity to power equipment onboard. This packet explains how sunlight can be converted directly to electricity.

The technology of silicon solar cells (others can be made from cadium-copper sulfide, cadium telluride, etc.) is the most developed and will be used as an example throughout this explanation. Silicon is in a special group of substances known as semi-conductors. (i. e. Silicon has some properties of both a conductor of electricity and an insulator).

Explanation:

1. Silicon has a valence of 4. (i.e. There are 4 electrons in the outer shell available to combine and thus there are 4 holes in the outer shell to fill.)
2. When silicon atoms are free to take up with other silicon atoms they form equidistant covalent bonds (sharing of electrons). They share an atom with each of their surrounding neighbors thus forming a stable crystalline structure.
   In this form, silicon is a perfect insulator in that no electrons are free to move if voltage is applied.



3. In metals, or good conductors, the electrons are not localized in such a way that binds specific pairs of atoms together, they are free to move within the crystal as an electric current when voltage is applied.
   In silicon, with the addition of light, the bond between an electron and the 2 atoms it binds will be broken, thus freeing the electron, (i.e. making it available for conduction). This reaction is known as the photo electric effect.

Silicon Solar Cells

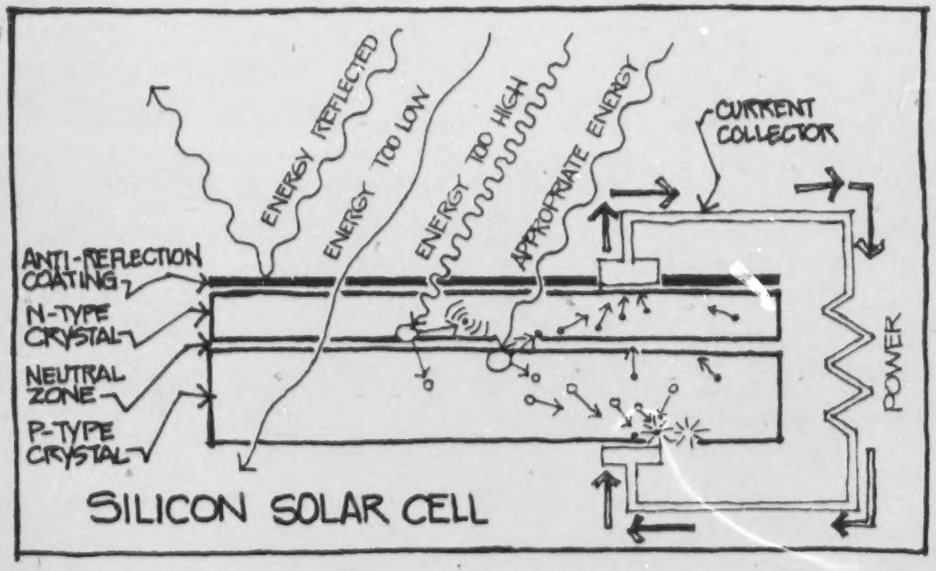
In silicon solar cells the silicon used is "doped". This means that instead of having a structure that is pure silicon, other substances are introduced to change the valence and to make the freeing and exchanging of electrons easier to produce.

Explanation:

1. N-type silicon has a valence of 4. If combined with a substance with a valence of 5, say phosphorus, the phos-

phorus will have an extra electron that is not shared with any of the 4 silicon electrons. This crystal is an N-type with a free electron - thus has a net negative charge.

2. P-type silicon has a valence of 4. If combined with a substance with a valence of 3, say boron, the boron will share only 2 electrons with 3 of the silicon neighbors and 1 with the fourth. This means there is a hole created for the addition of another electron. This semi-conductor is called a P-type crystal as it has a net positive charge.



A silicon solar cell is a wafer. It is a thin (.5 micron) layer of N-type silicon and a layer of P-type silicon sandwiched together. A conductive material, usually a silver wire, is set up to make contact with both the front and back layers of the cell. The junction of the N and P-type layers is known as the neutral zone. This is where the extra electrons from the N-type layer and the holes from the P-type layer migrate to form a neutral charge.

How is sunlight converted to electricity?

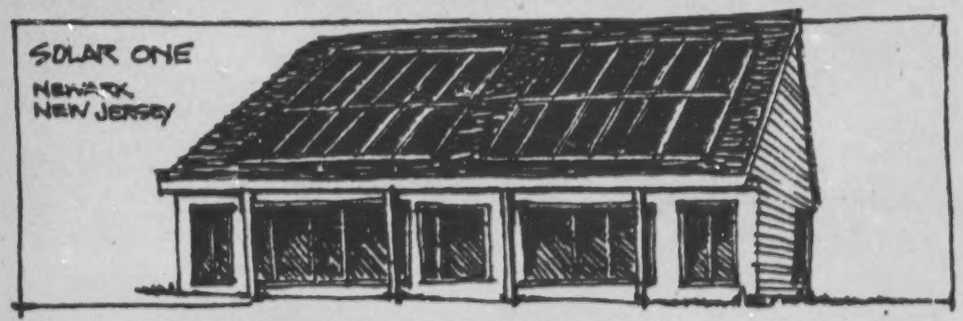
Explanation:

1. In the absence of light there is very little electron activity. However, light of a specific wavelength, 1.1 microns or less, will generate electron activity.
2. If a photon of light 1.1 microns in length (or less) strikes the solar cell it will actually penetrate the thin N-type level and strike near the junction of the 2 types of crystals (the neutral zone).
3. The photon of light has enough energy to dislodge one of the electrons, which leaves behind a hole.
4. The freed electron migrates into the N-type layer and the hole migrates into the P-type layer.
5. As the freed electrons accumulate, they travel to a low resistance current collector on the front surface of the cell, (the silver wire), generate an electric current in the external circuit, and then travel through to the P-type layer where they can recombine with the waiting holes.
6. If a photon of light has a wavelength greater than 1.1 microns, it will not have sufficient energy to free an electron. (Parallel discussion on wavelength conversion in solar collector packet). These photons pass right through the cell.
7. The energy from photons with a wavelength of less than 1.1 microns is absorbed by an electron. The electron can retain a maximum of 1.12 electron volts of the photon's energy, so that any excess is converted to heat.
8. Some photons are reflected from the front of the cell as it has an anti reflective coating.
   Other photons are blocked from entering because the current collectors cover part of the front surface.
   All these losses of potential energy mean that a silicon cell can ideally convert a maximum of 18% of the solar energy it receives into electrical energy.

How are solar cell units used as a supply of electrical energy?

At present there are several systems in which solar cells are used to generate electricity. As in all solar collectors there is a collecting surface, and a storage area.

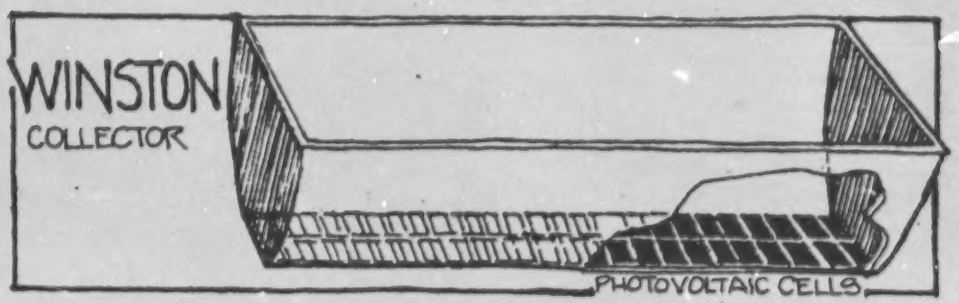
In the Solar One house, built in 1971 by the University of Delaware, solar cell panels are used. A typical silicon



solar cell will deliver maximum power at approximately 0.45 volts. Therefore, solar cells must be joined in a series in a solar panel to generate electricity sufficient to charge a 12 volt battery. The number of cells needed to generate a given amount of electricity is dependent upon the area of the individual cells and the intensity of radiation on any given area. The current increases as the area of the cell increases, however, in terms of production cost, and maximum voltage efficiency, it is not necessarily more efficient to use fewer, larger cells.

Another solar cell system is one employing a parabolic mirror. (Discussed in solar collector packet - concentrating collector sector). The output of the solar cell is proportional to the intensity of the radiation falling on it. If the radiation were concentrated, a smaller area of solar cells would be used to achieve maximum efficiency. There are several problems with the use of parabolic concentrators. For maximum efficiency, it is important that the radiation fall on the cell at a 90° angle to its front surface. With a parabolic mirror there are a variety of angles. Second, it would be necessary to rotate the reflector to keep it pointing at the sun throughout the day. As with solar panels, the electrical output can also be stored in a battery.

The Winston collector is another system utilizing solar cells. It is a trough shaped collector designed to concentrate a high proportion of incident sunlight on a strip of solar cells and has the advantage that it does not need to be rotated to track the sun.



Aside from the production of electricity, solar cells have another potential; they can produce heat. The electrons in the solar cells can only retain a maximum of 1.12 electron volts of the photon's energy that has been received. (Photons with a wavelength of 1.1 microns or less). The energy that cannot be stored in the electron (for potential production of electricity) is converted to heat. This heat can be drawn off the back surface of the solar cell and stored for use in space heating and cooling, and water heating. The electricity produced can aid in the transport of this heat. This principle is utilized in the Solar One house discussed earlier in this package.

Technology in Silicon Solar Cell Manufacturing

Although silicon is the second most abundant element on earth, solar cell formation requires that the silicon must be chemically pure and the crystallographic structure perfect. A choice of complex processes, that at present are very expensive, are used to deliver silicon in this form.

1. Czochralski Method - is based on dipping a rotating seed crystal into a crucible of molten silicon and slowly withdrawing 3.

it. The result is a massive, cylindrical crystal, 3-4" in diameter and several feet in length. Boron can be added to the melt to produce a boron doped silicon P-type. To produce N-type, one surface of a wafer of P-type is exposed to the phosphorous at a high enough temperature for phosphorous atoms to diffuse into it, and the wafer is converted.

To make wafers from the cylinder, the crystal must be sawn very slowly. In this process, a substantial portion of crystal is lost as dust. Finally, the electrical contacts are attached to the front and back of the wafer, an anti-reflective coating is applied, and the entire wafer is covered with a protective membrane.

2. EFG or Ribbon Process (Edge-Defined Film-Fed Growth) - This unusual process, for growing silicon solar cells, was developed in 1975 by Tyco Labs in Waltham, Massachusetts. The growth of these cells takes place as molten silicon rises by capillary action through a slot in a die made of graphite. A film of liquid silicon at the top of the die feeds the growing crystal. The ribbon of silicon is 1.5 centimeters thick and can be grown at a rate of 2.5 centimeters/minute. It can then be cut into rectangular wafers 2.5 cm. wide and 10 cm. long. The crystals made from this process are not as perfect in structure as those made from the Czochralski process, but are more efficient to produce.

Advantages

Solar cells are an exciting energy resource. They have the potential to produce electrical and heat energy using a free and perpetual energy source, the sun. At present, they could be very useful in areas with greater insolation that utilize electricity for sun created needs, such as, air conditioning and irrigation. They are the only method available for converting the sun's energy directly to electrical energy.

Disadvantages

Since sunlight is an intermittent energy source, and the amount of insolation varies greatly with location, solar cells are not universally suitable as an energy source. They must also be used in conjunction with a storage or back-up system. At present, solar cells have not gone into mass production and therefore killowat production is very expensive. As the need for developing alternate energy sources becomes increasingly apparent, mass production will follow and cost should go down. Another factor to be considered is the efficiency of solar cells. The maximum theoretical efficiency is 21%, however in actuality they are only about 12-18% efficient. This means that they are only able to utilize a percentage of radiation that falls on them. This figure should be put into perspective however. The automobile performs its energy conversion at an efficiency of less than 20% it performs its people-moving function at a far lower efficiency.

As the technology for solar cell production and utilization progresses, they should become a feasible and exciting resource.

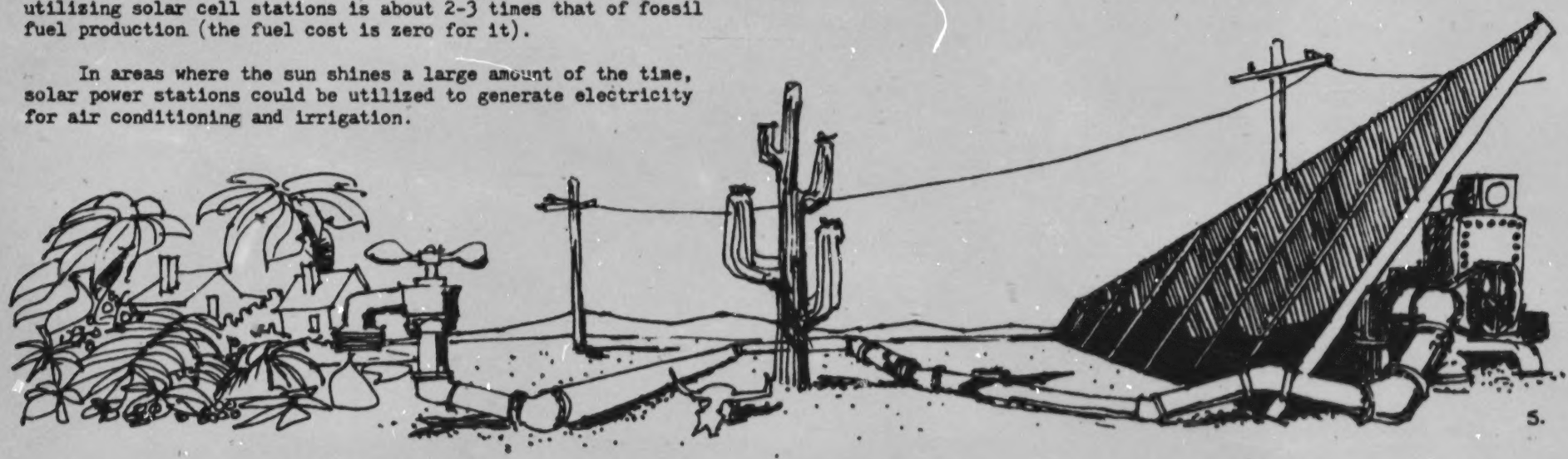
Outlook

What is the future of solar cells? Remember first that they have been in use since the 1950's. The problems now are their relatively low maximum efficiency, and the mismatch between the available electricity and the energy task. Three possibilities are being explored. The first is to set up large solar power stations in desert areas in the S. W. U. S. At a 10% efficiency a collecting area of 10 sq. km (a sq.3.16km/side), could generate a peak power of 1,000 mega watts; the amount of a typical fuel burning plant. This could not totally replace other methods of electrical production, however, as the source could not 4.

be relied on at all times. It would greatly reduce the demand on fuel burning stations. Another concept would also involve the use of solar stations but would take the energy created and store it for later use rather than direct use. The energy would be stored by pumping water into elevated basins; the energy would be retrieved by allowing the H_2O to return to it's original level through turbogenerators. Another storage method would be to manufacture hydrogen through electolysis of water. The hydrogen could later be burned, or fed into fuel cells to generate electricity. A third system would be to position solar cell panels on orbiting space stations. The energy could be transmitted to receiving stations on earth by the microwave beams. The advantage of this system would be that the sun would be constantly available and because of the location, the sun's radiation would be twice as intense. A drawback could be possible danger caused by beaming microwaves towards earth.

The future of solar cells is going to be determined largely by cost. If the technology for manufacturing solar cells can be stepped up to a large scale level, the cost will go down. The price of fossil fuels will also determine the need for this stepped up development. At present the k.w. production cost utilizing solar cell stations is about 2-3 times that of fossil fuel production (the fuel cost is zero for it).

In areas where the sun shines a large amount of the time, solar power stations could be utilized to generate electricity for air conditioning and irrigation.



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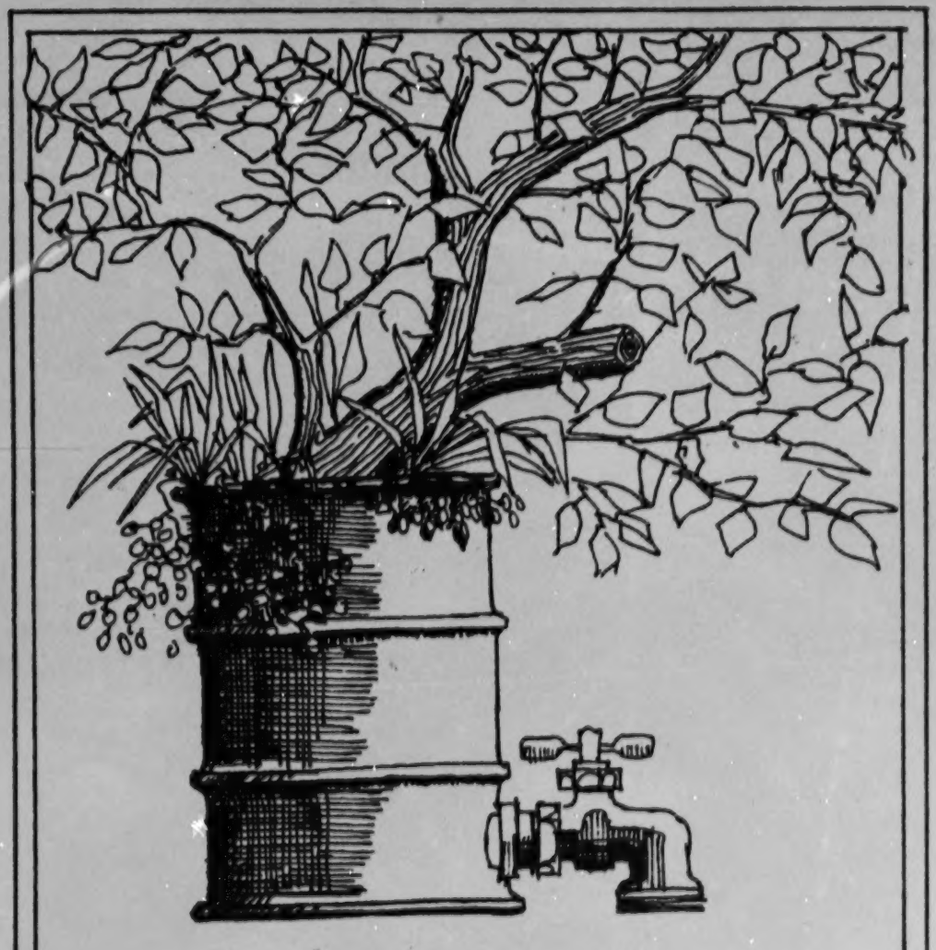


BIOCONVERSION

Bioconversion

Concepts:

- Photosynthesis
- Respiration
- Food Chain

Overview

Solar energy is trapped by green plants and through photosynthesis, is converted to chemical energy which is stored in the plant. (Solar cells convert solar energy to electrical energy.) Bioconversion is the process of releasing this stored chemical energy and converting it to biofuels. The plant must be eaten, burned, or decayed, in order to release this carbon based chemical energy. Biofuels differ from the non-renewable fossil fuels in that they come directly from living organisms, and are continuously being produced. Both are ultimately derived from plants; the only renewable source of chemical energy.

This packet briefly discusses the energy flow in the biosphere and the conversion of chemical energy into several bio fuels.

Photosynthesis and Respiration

Photosynthesis and respiration are the basic metabolic processes of most living plants. The energy for these processes comes from sunlight.

In photosynthesis, energy from light is used to remove carbon dioxide (CO_2) and water (H_2O) from the environment. For each molecule of CO_2 and H_2O removed, a molecule of carbohydrate CH_2O is produced and one molecule of oxygen (O_2) is returned to the biosphere.

In respiration by a plant or an animal, the combustion of carbohydrates and oxygen produces ATP, CO_2 and H_2O, thus

these two reactions are interdependent. Photosynthesis utilizes the CO_2 produced by respiration while respiration utilizes oxygen produced by photosynthesis.

ATP is the key to the energy exchange in these processes. It is the chemical compound adenosine triphosphate which is formed by the chemical union of adenosine diphosphate and one free phosphate molecule during the metabolic processes of photosynthesis and respiration. ATP is the unit in all living things that transports energy from one part to another.

As mentioned earlier, this chemical energy stored in plants can be released in several ways. In terms of the energy flow in the biosphere, the food chain accounts for the release and utilization of much of this energy. The food chain is defined as the passing of energy and nutrients through a series of organisms. There is an energy loss, through conversion of about 90% at each level in the chain.

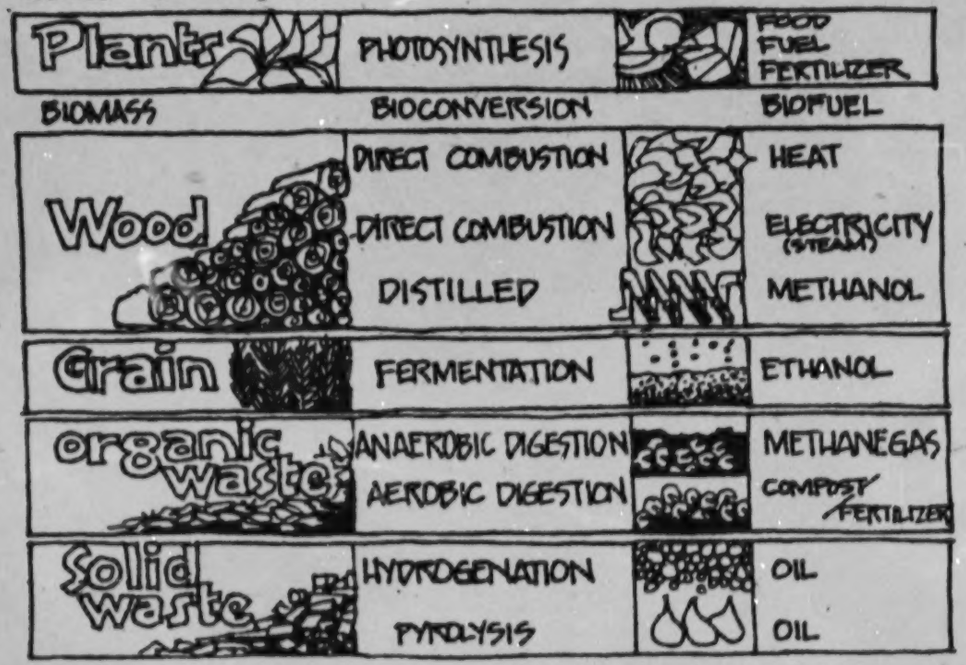
Explanation:

1. Herbivores (or plant eaters) feed on the carbohydrates and proteins generated by photosynthesis and stored in green plants.
2. Carnivores (or meat eaters) feed on herbivores.
3. Decomposing organisms feed on both plants and animals (and their waste products) so that the original matter and nutrients are returned to the soil and water.
4. The plant utilizes the soil and water to aid in its growth.

This in effect completes the cycle of nutrients and matter from plant back to plant, but it is essential to understand that the energy flow is unidirectional and non-cyclic (matter cycles, energy flows). The sun generates the energy needed to produce the chemical energy in plants which is released to produce other forms of energy.

Energy can also be released and converted to biofuels. This packet discusses the forms of biomass conversion and conversion of wastes (originally from biomass to biofuels). It is important to understand that energy production from biofuels is far less efficient than from fossil fuel. However, plant growth is relatively fast, occurs at little or no cost, and most importantly is the only renewable source of carbon fuel.

The following chart lists the conversions that will be discussed in this packet.



WOOD

Concepts:

- Pyrolysis
- Combustion
- Endothermic
- Exothermic

Wood, like green plants, contains the stored chemical energy from photosynthesis. This energy is stored in carbohydrates (compounds made from carbon, hydrogen and oxygen) which can later be broken down. Several processes can be utilized to convert wood to biofuels. This packet discusses direct combustion, pyrolysis, and distillation of wood.

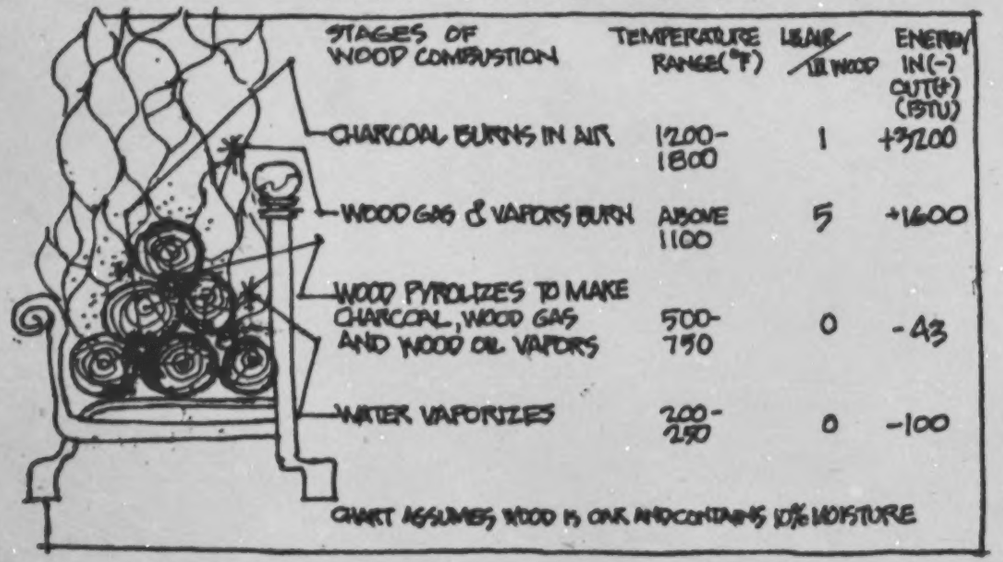
Wood is composed principally of carbon, hydrogen and oxygen which are stored in the cellulose and lignin. In complete combustion, all the carbon is converted to carbon dioxide and all the hydrogen is converted to water.

There are four stages in the combustion of wood. Each stage occurs with certain parameters, dictated by temperature and oxygen flow. Different end products are produced during each stage of combustion. These end products are in turn used for each successive stage. The first two stages occur with a net energy loss; i.e., an excess of energy is used in order for them to occur. The second two stages produce energy.

1. The first stage in direct combustion is the vaporization of water. Wood is ignited and heated to within a range of 90-120°C (200-250°F). The hygroscopic bond between the wood and the water is broken and the water evaporates, becoming a gas. This stage is endothermic, i.e., it requires energy to occur. Approximately 1150 Btu's/pound of water driven off is used. About 100 Btu's are used to break the bond between the water and wood, and approximately 1050 Btu's are used to vaporize the water. It can thus be estimated that wood with a 10% moisture content uses 100 Btu's/pound, for vaporization to occur.
2. The second stage is known as pyrolysis. This stage is broken into two parts.

a. As the temperature of the wood is raised to within a range of 100° - 280C° wood gasification occurs. A small amount of H_2O is drawn off, and carbon dioxide carbon monoxide, formic acid, acetic acid, glyoxal and other compounds evolve. All these compounds are combustible with the exception of H_2O and CO_2. They prevent combustion of the other components because their concentration is too high. This stage is also endothermic requiring an estimated 43 Btu's/lb. of wood with a 10% moisture content.

b. This phase of pyrolysis occurs in the range of 280-500°C (540° - 900°F). The reactions occuring in this step are exothermic, they give off heat. The temperature of the wood rises and large amounts of gases, wood tar and charcoal are generated. The gases include, carbon monoxide, methane, methanol, formaldehyde, hydrogen. Formic and acetic acids, carbon dioxide, and water vapor, are also formed. The combustible components in this mixture are sufficient for ignition and as the temperature nears 500°C (900°F) the pyrolyis stage is completed, leaving charcoal, which is mostly carbon, as the end product.



3. The third stage is the burning of the charcoal. Charcoal can not burn without oxygen which can not get to the surface while the gases are escaping from the wood. As the temperature nears 500°C, the flow of gases subsides, oxygen becomes present, combines with carbon (from the charcoal) to form carbon dioxide and carbon monoxide. Carbon monoxide is a combustible gas. This reaction is exothermic, producing approximately 3200 Btu's/lb. of wood with a 10% moisture content.

4. The fourth stage is also exothermic. It occurs at a temperature over 500°C and is the burning of wood-gas and vapors. This stage produces approximatley 1600 Btu's/lb. of wood with a 10% moisture content. The end product for this stage is wood ash.

All of these stages of combustion and pyrolysis can occur simoultaneously. The temperature ranges given here are provided as a guideline to the various stages in combustion and pyrolysis and are not neccessarily rigid. Because of differing abilities to transfer the heat produced in combustion to surroundings, and because of varying abilities to burn volatile gases, fireplaces and stoves have varying efficiencies.

The end product for combustion is heat. This heat can be used directly or it can be converted to steam to produce electricity.

Electrical generation from wood, most often utilizes wood waste as it's biomass. This wood waste; bark, leaves, etc., are reduced to a uniform size and machine fed into a furnace. They are burned (as in the process discussed above) and the heat is then converted to steam which powers a turbine that produces electrical energy.

This system is particularily appropriate for areas with a wood-oriented industry. The waste products from the industry are used to provide electricity for the mill. The remaining wood ash is then utilizable as fertilizer and should be spread on the forest floor to assure a cycling of nutrients.

Advantages:
Efficient burning of wood is virtually pollution free with complete combustion, producing CO_2 and H_2O. Wood is a renewable resource - a from of stored solar energy. With careful forest management, recycling of nutrients, and complete combustion, wood supplies should last indefinetely. Burning wood is an excellent source of heat for space and water heating. It is a good way to use the waste products of commercial logging to generate power for their operations.

Disadvantages:
Large scale "energy farms" may create ecological imbalances: monocultues are prone to disease and pests, wood is bulkier than "conventional" fuels. The equipment used for the combustion of wood is also more expensive than that of fossil fuel plants.

Outlook:
Good! Waste in logging operations alone could provide enough to replace 21% of the total fossil fuel used nationwide- including 50% of the oil and gas owned by U.S. utilities. The annual growth of Maine's forests alone is enough to provide the electricity needs of the state along with a large margin for increase.

METHANOL

Methanol is another biofuel that can be made from wood. There are two conversion processes which will yield methanol. This section discusses both the distillation and decomposition of wood.

Distillation
Explanation:

1. Raw wood is dried and placed in ovens connected to condensors.
2. Materials are heated to 500°C.
3. The gases that are produced are condensed.
4. The condensed materials are stored in tanks. They consist of tar which settles to the bottom of the tank, and pyroligneous acid. Pyroligneous acid consists of acetic acid, 4% methanol acetone and allyl alcohol.

5. Pyroligneous acid is distilled to remove tar.
6. Acid is neutralized with lime leaving acetic acid and alcohol.
7. Alcohol is distilled from acetic acid, leaving acetic acid liquors and crude alcohol.
8. The product is distilled to form methyl alcohol.

Decomposition
Explanation:
1. Wood or any carbonaceous fuel is continuously dumped into a furnace.
2. Oxygen is injected, causing combustion.
3. Hot gases escape through the descending wood.
4. Wood is decomposed yielding gas-

$$2C + 2H_2O \text{ (gas)} \rightarrow 2CO_2 + H_2 \text{ (in 2: 1 ratio)}$$

5. Ratios of CO_2 and H_2 are physically reversed.
6. Gases are compressed, passed over a catalyst and a reaction occurs changing gas to methanol.
7. $CO=2H_2$ CH_3OH.

About 400 tons of wood is used to make 150 tons of methanol. Methanol can then be burned as a liquid fuel. It can be substituted for gasoline or blended with it. Methanol can also be used in fuel cells or as a fuel in power generating plants.

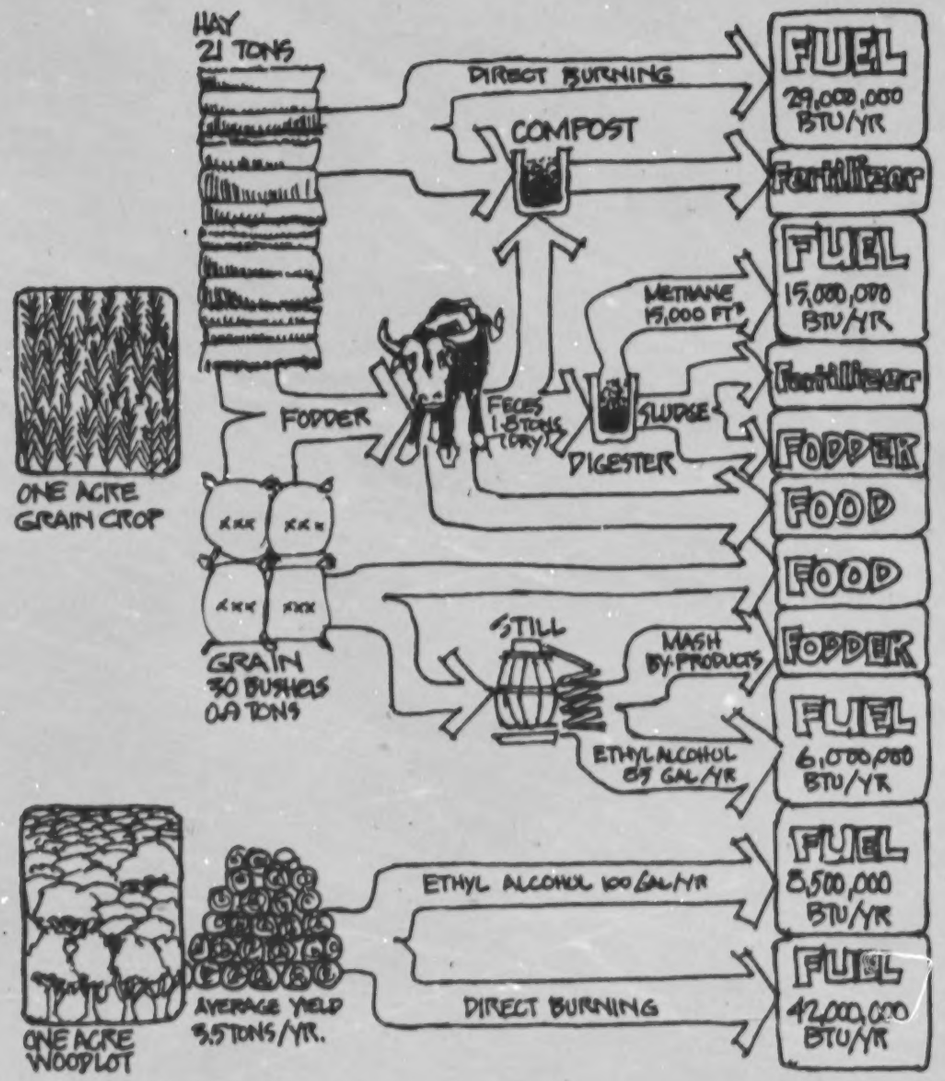
Advantages:
Methanol is a very clean burning fuel. It can be used for a variety of purposes, including fuel for automobiles. Methanol can be stored and shipped more easily than raw wood. It may provide a good solution for a fuel shortage. Methanol can be prodcued from a variety of materials including organic wastes. Methanol can be blended or mixed with gasoline so as to be used as a fuel extender.

Disadvantages:
Very large areas of wood are needed to produce large quantities of methanol. A lot of energy is used in the process. It would be more efficient to burn the wood directly instead of converting it to another fuel first.

For example, an acre woodlot might yield about 3.5 tons of wood a year. If this were burned directly it would yield about 42 million Btu's. If the wood were converted to alcohol and then burned, it would yield only about 8.5 million Btus, over 75% less energy. Creating large energy "farms" to intensively grow monocultures such as a specific fast growing tree may create several ecological problems.

Outlook:
Methanol has been used as a fuel since about 1830 when it was burned in lamps. During WWI and II, methanol was distilled from wood and used as a substitute for gasoline. In 1938, nearly 9,000 wood burning cars were in use. Methanol was used in racing cars in the 1920"s. Currently research is being undertaken to use methanol as a gasoline substitute. It is believed that because methanol can be made from a variety of sources, (including coal) and it may one day be fuel for our cars.

The following diagram illustrates the efficiency of bio-conversion using 1 acre of woodland and 1 acre of grains for comparison. Note the different conversions that are possible and the presence of the food chain.



GRAINS

Concepts:
Hydrolysis
Fermentation

Grains, sugar crops (sugar beets, cane sugar, etc.) and cellulose can be converted to ethanol by the distillation of plant sugars. Either the raw material contains sugars that can be fermented directly (sugar crops), or they contain carbonhydrates (grains and cellulose) that must be broken down before the conversion can occur.

How can grain be used for fuel for your car engine?

Explanation:

1. Plants are finely ground or heated in water to form a mash.
2. The enzyme diatase converts the mash into a sugar solution by hydrolysis. (Hydrolysis occurs when the molecules take on water and they break apart into the original sugar molecules.) Diatase is found in all sprouted grains. The grains are often sprouted before they are fermented.
3. Yeast is added to the mash. Yeast contains another enzyme, zymase, that ferments the sugar to produce ethanol and CO_2.

$$C_6H_{12}O_6 \xrightarrow[\text{enzyme}]{\text{zymase}} 2C_2H_5OH + 2CO_2$$

Temperature must be monitored carefully in these processes for the successful growth of yeast.

The following table indicates the efficiency of different conversions yielding ethanol.

From simple sugars (fruit sugars)	51.1%
From complex sugars (maltose, sugar beets)	53.8%
From starches (grains)	56.8%

Alcohol is a very volatile fuel with a high BTU content: 84,000 BTU/gallon as compared with 135,000 BTU/gallon for gasoline. Alcohol also has an octane rating of 99. It would be suitable as a substitute for gasoline in cars or it can be used as a blend.

Advantages:

Fermentation is a simple and well understood process that produces a useful volatile fuel. It uses a renewable resource (grain and sunlight). The fuel produced is relatively non-polluting.

Disadvantages:

Ethanol production suffers from deficiencies of bioconversion loss of energy through transfers. Wouldn't it be easier to use the sun's energy directly? It is difficult to rationalize using valuable food crops in order to drive more cars.

Outlook:

Although in some parts of the world ethanol is presently used as an additive to gasoline, the practicability of widespread use is not in the immediate future. Our need for food from the grains we produce far exceeds our need for fuel.

ORGANIC WASTE

Concepts:
anaerobic digestion
aerobic digestion

Manure and crop wastes, which were once plant matter, can be converted to produce two useful end products. The first conversion occurs anaerobically (in the absence of oxygen) and produces the biofuel methane gas. The second conversion occurs aerobically (in the presence of oxygen) and produces fertilizer

and compost. At present, use of these conversions processes is best suited to a farm community where there is a constant supply of waste materials and a demand for the end products.

Anaerobic Digestion

Manure and crop wastes can be converted to methane, the primary component of natural gas. While natural gas yields between 1100 and 1200 BTU's/ft^2. The reason for this difference is that natural gas is about 80% methane and biogas averages about 54-70% methane. The remaining gases include carbon dioxide, hydrogen and nitrogen with traces of carbon monoxide, oxygen and hydrogen sulfide.

Different forms of waste has varying potentials for the production of methane. Following is a chart that give figures for methane production. These are based on a per pound of manure anount of methane produced according to the material used.

1 lb. material	Biogas (ft^2)
pig manure	6.0 - 8.0
cow manure	3.1 - 4.7
chicken manure	6.0 -13.2
conventional sewage	6.0 - 9.0

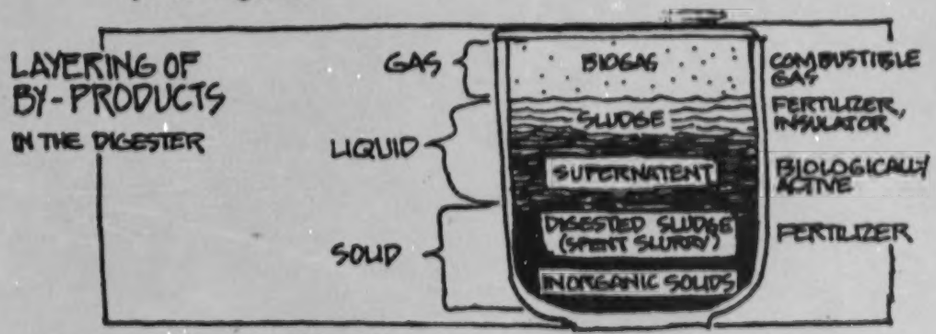
From Methane Digestors for Fuel Gas and Fertilizer (Merrill and Fry)

How are manure and crop wastes converted into methane?

Explanation:

This process is carried out in a methane digestor - a closed tank. Essentially it involves two groups of bacteria in the absence of oxygen. One group breaks down the wastes into organic acids and a second converts these organic acids to methane (CH_4) and carbon dioxide (CO_2).

1. A slurry of water and waste is loaded in a digestor. It is essential that this slurry contains a correct proportion of carbon and nitrogen. This proportion is 30% carbon/1% nitrogen. This specific proportion is ideal for the growth of anaerobic bacteria. The temperature should be 35°C (95°F) to promote proper bacteria growth.
2. Acid producing bacteria secrete enzymes that break down the fats, proteins and carbonhydrates contained in organic waste. The end product is organic fatty acids, mostly in the form of acetic acids.
3. Methane producing bacteria break down these acetic acids to form methane and carbon dioxide.
4. As the methane gas is produced, it rises and accumulates on the surface of the mixture. The gas may be burned directly, stored, or compressed to power engines.



There are several by-products from this conversion. These include:

Biogas - 70% CH_4, 29% CO_2, traces of O_2 and H_2S.

Scum - Coarse mixture of firbrous materials, released from raw material. Can be used to insulate digestor (to maintain temperature) and as fertilizer.

Supernatant - Spent liquids of original slurry.

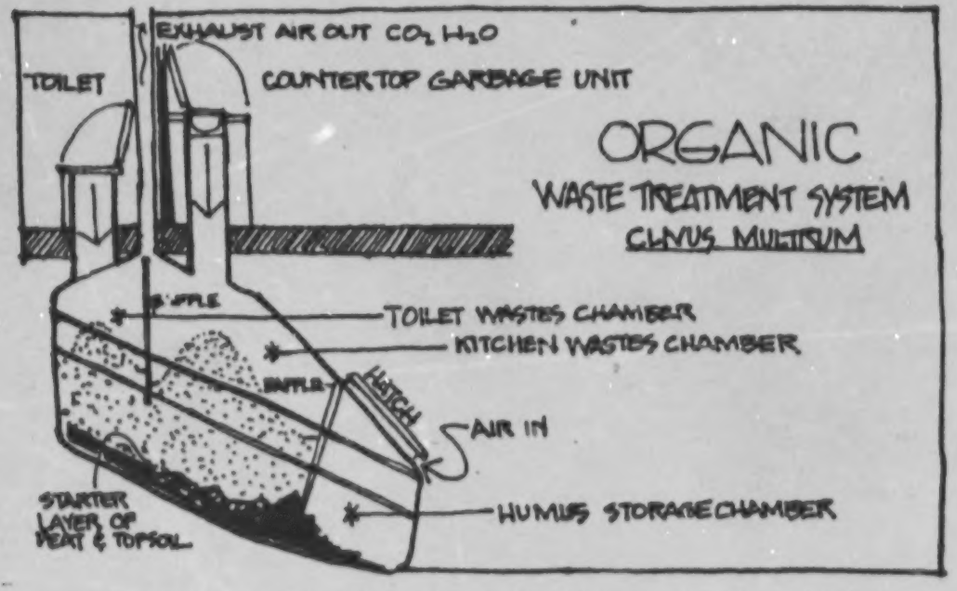
Sludge - Spent solids of original slurry. It is reduced to 40% of original volume. This sludge can be used as fertilizer.

Inorganic solids fall to the bottom.

Aerobic Digestion

Also known as compost'- , aerobic digestion produces little directly usable ene_ y. The contribution of aerobic digestion is in the form of fertilizer. This is important as this fertilizer can repl ce chemical fertilizers which are major consumers of fossil fuels (principally natural gas). Aerobic digestion completes the cycling of matter and nutrients in the same manner as decomposition discussed in the food chain.

A specific form of an aerobic digestor is the clivus multrum composting toilet. (MAS building utilizes this system). The clivus composts human and vegetable wastes with an end-product of humus.



The clivus multrum consists of a holding tank situated at an angle allowing the waste to slide down the sloping botton slowly. This slow rate ensures that the waste will be decomposed by the time it reaches the storage area. A draft is maintained by natural convection providing oxygen for decomposition. Carbon dioxide and water vapor are the chief waste products of the aerobic bacteria thus the vent gases are not harmful. The humus which reaches the storage area is only 5 - 10% of the original volume of waste. The other 90 - 95% are the waste gases. This humus can be used directly as fertilizer or soil enrichment.

Advantages:

Digestion provides a use for organic wastes, paper, food, human and animal wastes and is an indirect form of recycling. Final product is sludge which is an excellent fertilizer. Methane digestors are simple and easy to build. They can be built on very large or very small scales. Since there is a tremendous amount of fuel-waste (especially in cities) methane digestors can provide a substantial supplement to our diminishing natural gas supply.

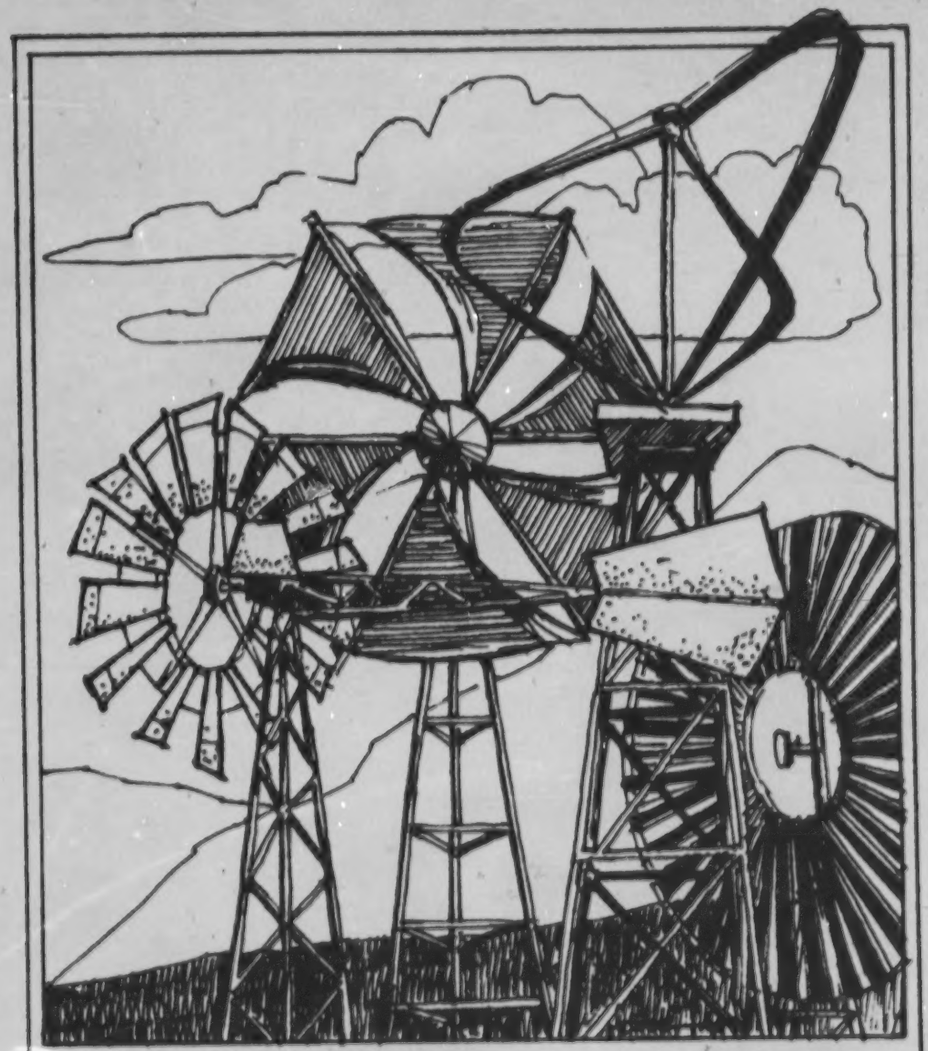
Disadvantages:

It takes a large amount of material to make a small amount of gas. It would, for example, take waste from 60 chickens or 8 persons to produce enough gas to cook simple meals for one person. Directing efforts towards digestion of organic matter and sewage may divert attention away from real energy savers, recycling of paper, composting of vegetable matter and reduction of sewage. It would be cheaper and more efficient to recycle than to build massive plant to treat more wastes.

Outlook:

Digestors are already successfully being used in many places around the world (in India they are widely used). They are especially useful near animal farms where large amounts of organic wastes are produced. For this reason, they are excellent solutions for both fuel and waste problems in rural countries. Sewage treatment plants in cities have been digesting wastes and producing methane as a by-product to run machinery in the plant. Methane digestors provide a good use for what historically has been considered useless. Methane may someday provide 10 - 20% of our nation's natural gas requirements.

The Environmental Energy Education Project
The Maine Audubon Society
Gilsland Farm
118 Old U.S. Route # 1
Falmouth, Maine 04105



WIND

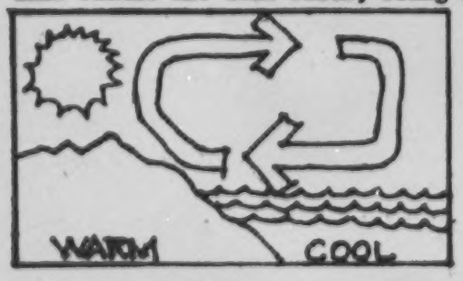
Wind

Anyone who has observed the destructive effects of a hurricane can have little question as to the power available in the wind. One U. S. Government study concludes that a major U. S. development program in wind power could supply up to 1.5 trillion kilowatt hours of electricity per year[1], or 100% of the 1970 U. S. electrical demand[2], while a second study arrives at a figure of 5 to 23% of the projected demand for the United States in the year 2000.[3]

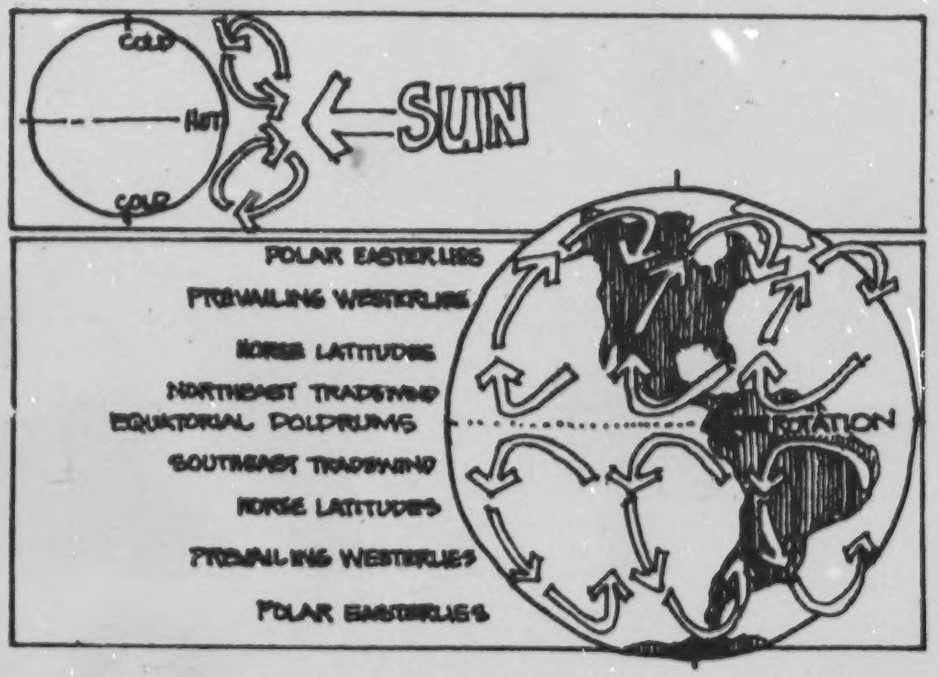
More important than the discrepancy in the calculation of wind power potential is the fact that the wind has for centuries provided a renewable and inexhaustible supply of energy. A closer examination of windpower theory and practice will allow the student to come to his or her own conclusions about the future viability of this resource.

Where Does the Wind Come From?

The wind is a form of solar energy, caused primarily by the uneven heating of the earth's surface by the sun. During the day the air over the water is cool, as the sun's energy is either evaporating water or being absorbed by it. The air over the land is heated more during the day, because the land absorbs less sunlight than the water. The warmer air over the land expands and rises, being replaced by the cooler, denser air from over the water. At night this cycle is reversed, as the water and the air above it tend to retain heat longer than the air over the land. This warmer air then rises, being replaced by the cooler land air.



Similarly, circulating planetary winds are caused by the greater heating of the earth's surface near the equator than near the poles. This results in colder surface winds blowing from the poles to the equator to replace the hot air that has risen over the tropics.



These planetary winds are also affected by the rotation of the earth. The cooler air moving from the poles to the equator is diverted by its own inertia toward the west, while the warmer air in the upper atmosphere is diverted toward the east. These effects create large counterclockwise circulation of the air around low pressure areas in the Northern hemisphere and clockwise circulation in the Southern hemisphere.

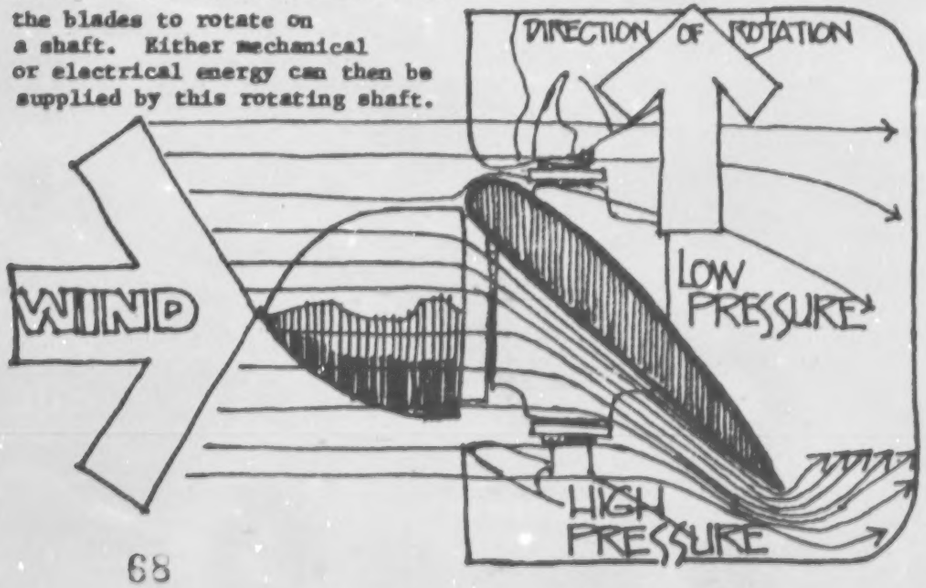
Finally, the tilt of the earth's axis of rotation about the sun results in seasonal variations in the strength and direction of the wind at a given site.

1

How is the Kinetic Energy in the Wind Coverted to Mechanical Energy?

A wind energy conversion system (WECS) converts the kinetic energy in the wind to mechanical energy which may be utilized for a number of electrical or mechanical functions.

This conversion from kinetic to mechanical energy is usually accomplished by the same forces that cause a sail to propel a boat or a wind to provide aerodynamic lift to an aircraft. This lift principle is illustrated in figure 3, which shows an airfoil designed to increase the pressure of the air passing on the underside of the blade, while decreasing the air pressure passing over the upper surface. This pressure differential is created in two ways: first by tilting the wing slightly up at the front so that the oncoming air hits the underside of the wind and slows down, thus increasing its pressure, and second, by shaping the airfoil to require the oncoming air to travel a longer path over the upper surface of the blade, thus reducing its pressure. The higher pressure, denser air on the underside of the airfoil actually pushes the blade into the region of lower pressure and density located above the upper surface of the blade. This pressure differential causes the blades to rotate on a shaft. Either mechanical or electrical energy can then be supplied by this rotating shaft.



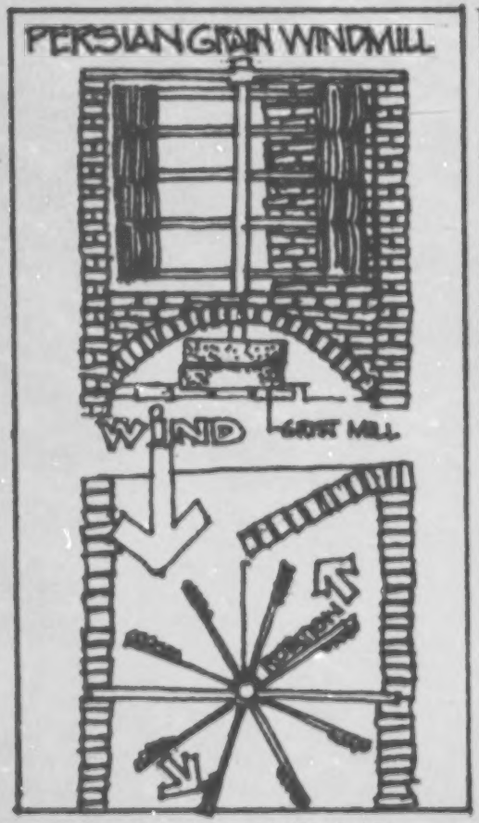
What is the Nature of the Power Available in the Wind?

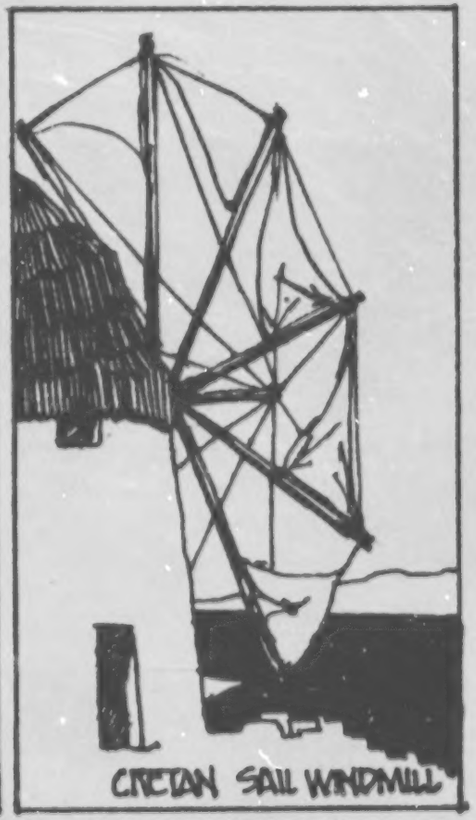
In working with the formula which determines the power available in the wind, or the rate at which energy is converted, four important parameters emerge which significantly affect modern WECS designs:

1. Because the wind must flow <u>through</u> a turbine, all of its energy cannot be extracted. Professor A. Betz, working in Germany in 1927, determined that the maximum amount of power which can be extracted from a wind stream by a turbine is 59.3% of the total power theoretically available. This figure is appropriately known as the Betz Coefficient.
2. Because the area of the turbine increases as the square of the diameter, power available from a wind machine will quadruple when the blade length is doubled.
3. A doubling of the wind velocity will increase the output of the WECS by eight times. This function, known as the cube law, is arrived at by combining the formula for kinetic energy contained in a mass of air ($KE = \frac{mV^2}{2}$) with the formula for determining that mass (m) as it passes through the area swept by the turbine (A) over a period of time (T) at a specific density (P). The formula thus becomes $P = \frac{\rho AV^3}{2}$. Thus, as wind velocity is doubled, raising it to the third power results in an eight-fold increase ($2^3 = 2 \times 2 \times 2 = 8$). WECS are generally designed to operate at windspeeds above 10 mph, where sufficient power is available from the wind, and below windspeeds of 50 mph, above which significant structural damage can be done to the WECS.
4. The faster the tip of a rotor blade turns in relation to the speed of the wind, the higher the aerodynamic efficiency of the WECS. This relationship, known as the tip-speed ratio, bears directly upon the power coefficient, or C_p, which is the ratio of the power extracted by a wind machine to the power available in a windstream. This power coefficient approaches the maximum of 0.59 when the tip-speed ratio reaches a value of 5 or 6.

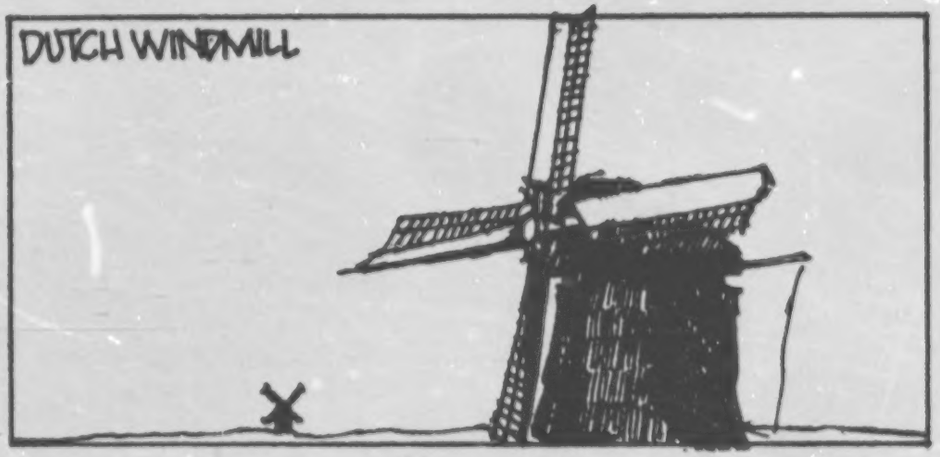
What are the Various Types of WECS?

1. Persian Grain-Grinding Windmill — probably the first wind turbine, used around 200 B.C. for grinding grain. A vertical-axis device, it used bundles of reeds rather than cloth for its sails.



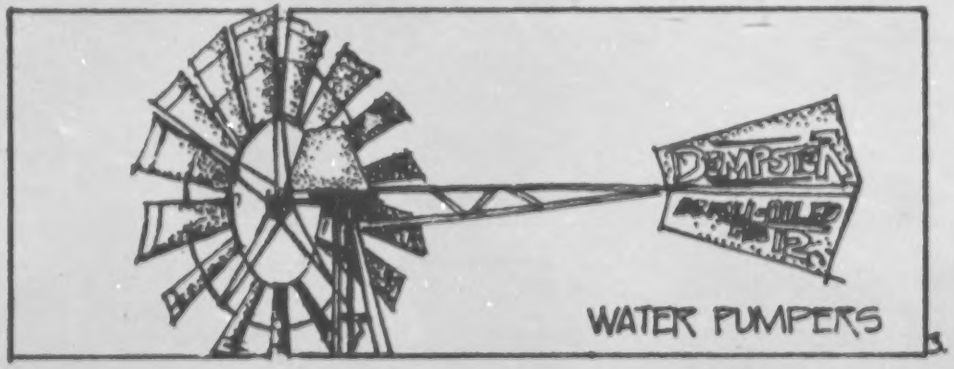


2. Cretan Sail Windmill — a horizontal-axis device; the sails could be manually furled depending upon the wind-speed. Over 10,000 of these devices are still in use on the island of Crete for pumping water or grinding grain.

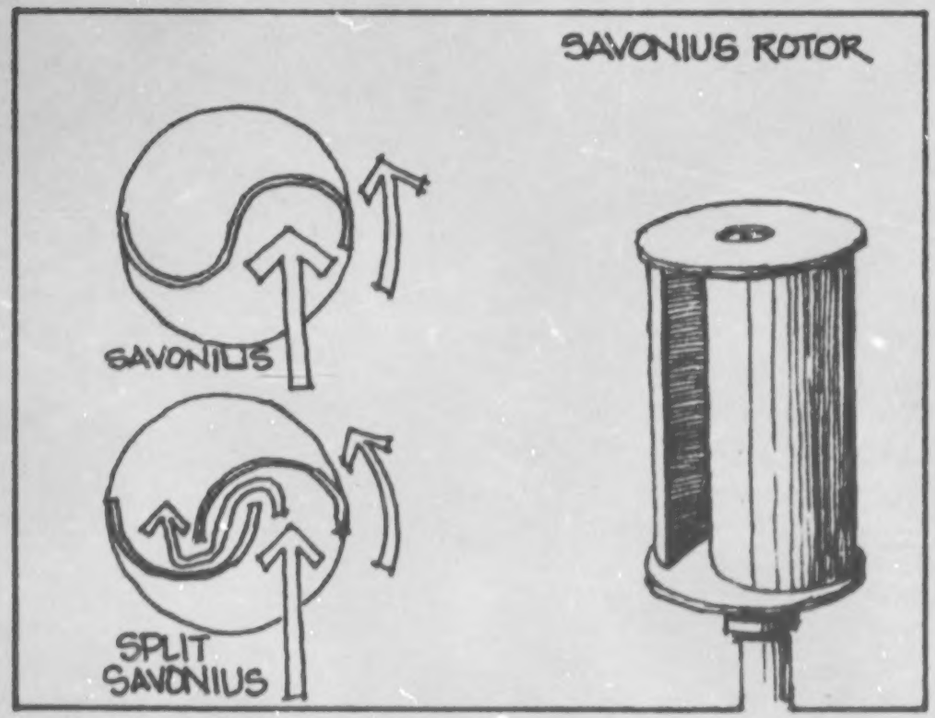


3. "Dutch" Windmill. These mills were used to grind grain, drain water from lowlands, and operate sawmills and papermills. By the mid-nineteenth century, some 9000 of these windmills were in use in the Netherlands. The C_p of this type of machine was in the area of 0.17. Power output was up to 90 HP or 67 KW.

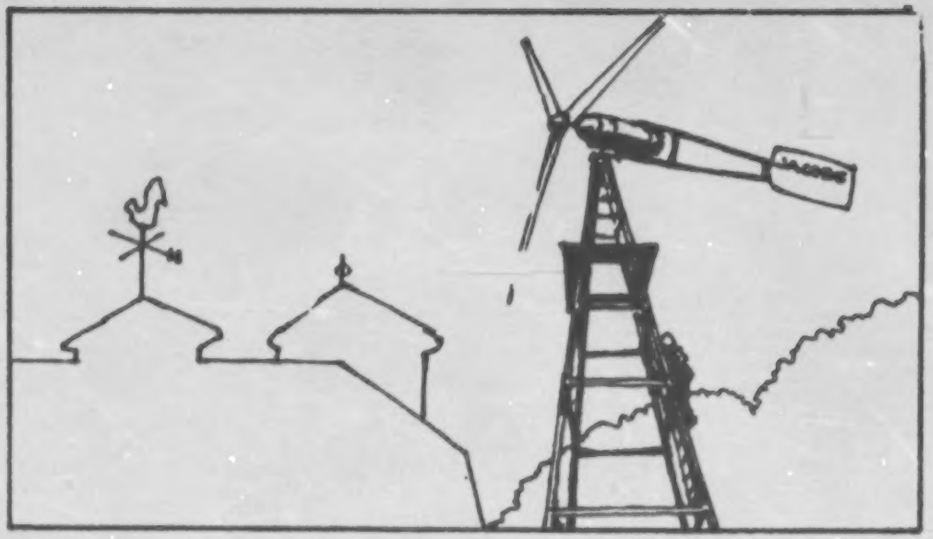
4. Water Pumper. From 1850 onward, more than 6 million of these windmills were built and used. 150,000 remain in operation today. The C_p of this type of machine is in the area of 0.15; power output is under 1 HP or 750W.



5. Savonius Rotor — This design, patented in 1929, is simple to make but aerodynamically inefficient. It is predominantly a drag device, meaning that it is largely pushed by the wind rather than providing lift force. Because it is able to travel only slightly faster than the wind, it is not able to produce significant amounts of power relative to its size, weight and cost.

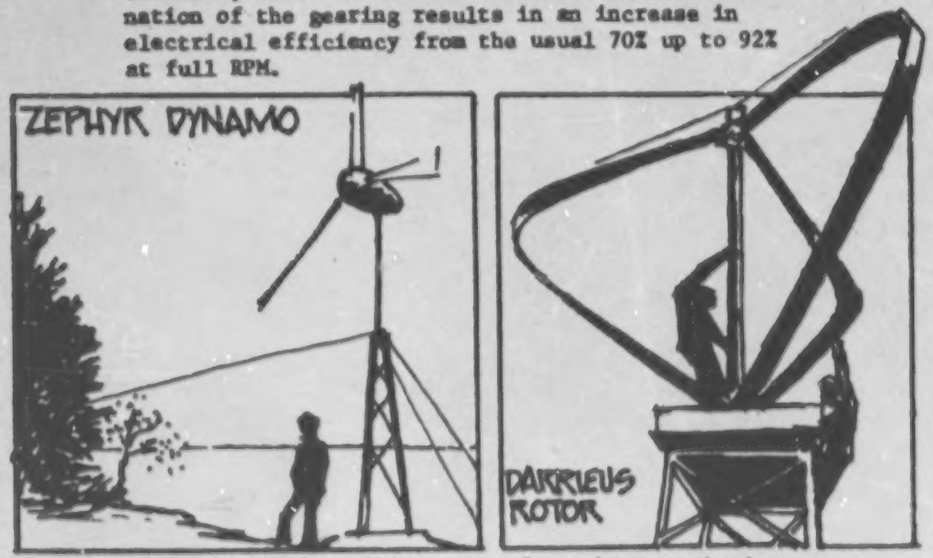


It is important to note that the above-described WECS are designed to produce high torque at low RPM to supply mechanical power. The following machines are designed to provide low torque and high rotational speeds for the production of electrical power by turning a generator or alternator.



6. Horizontal Axis-Upwind WECS. The Jacobs Windplant, build in the mid-1920's, featured 3 blades to minimize vibration, and a flyball governor to turn the blades edgewise to the wind in high winds. The blades were located upwind of the tower, requiring a tail to orient the machine into the wind. The quality of the design is legendary, with minimal maintenance required over periods as long as 30 years. With the system, including WECS, tower, batteries and other necessary equipment priced at about $1000, Jacobs sold about $75 million worth of equipment before his company closed its doors in 1957. While Jacobs had greatly helped to electrify the rural United States, his business was all but eliminated by the advent of cheap electricity from Rural Electrification Administration (REA) subsidized power facilities. While the Jacobs design is as functional as ever, the material employed in the construction of the windplants makes their prices extremely high. A rebuilt 3.2 KW Jacobs windplant without tower, batteries or installation, sells for approximately $5000. The C_p of this type of machine is in the area of 0.47.

Horizontal Axis-Downwind WECS — This design places the turbine downwind of the tower, eliminating the need for a tail and reducing gyroscopic forces on the turbine. One of the largest of this type of machine is the Zephyr Wind Dynamo, rated at 15 KW in a 30 mph wind. While most electricity-generating WECS employ a turbine turning at approximately 300 RPM connected through a gearbox to an alternator or generator which must turn at 3600 RPM, the Zephyr uses a turbine coupled directly to a low-speed alternator, both of which turn at 300 RPM. The elimination of the gearing results in an increase in electrical efficiency from the usual 70% up to 92% at full RPM.

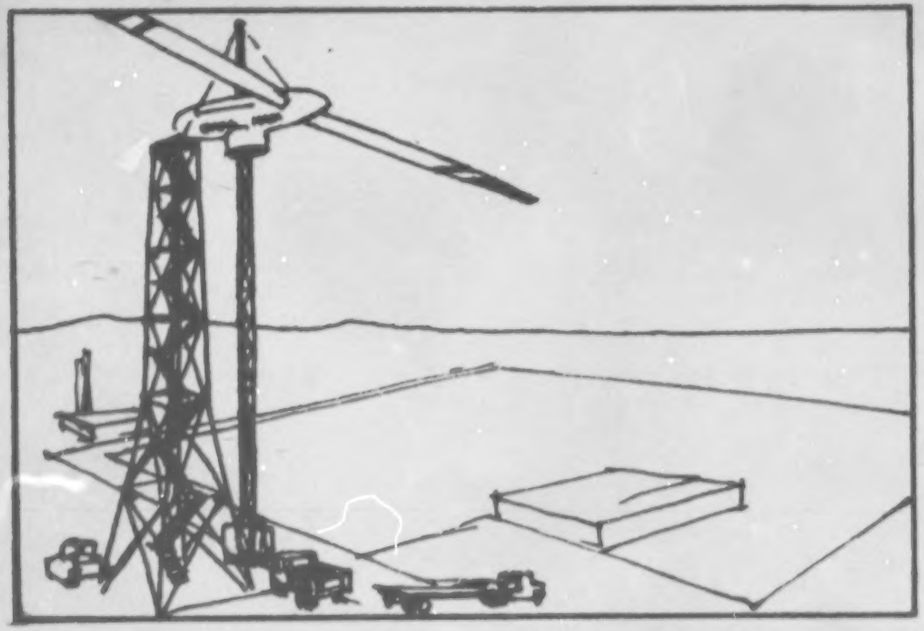


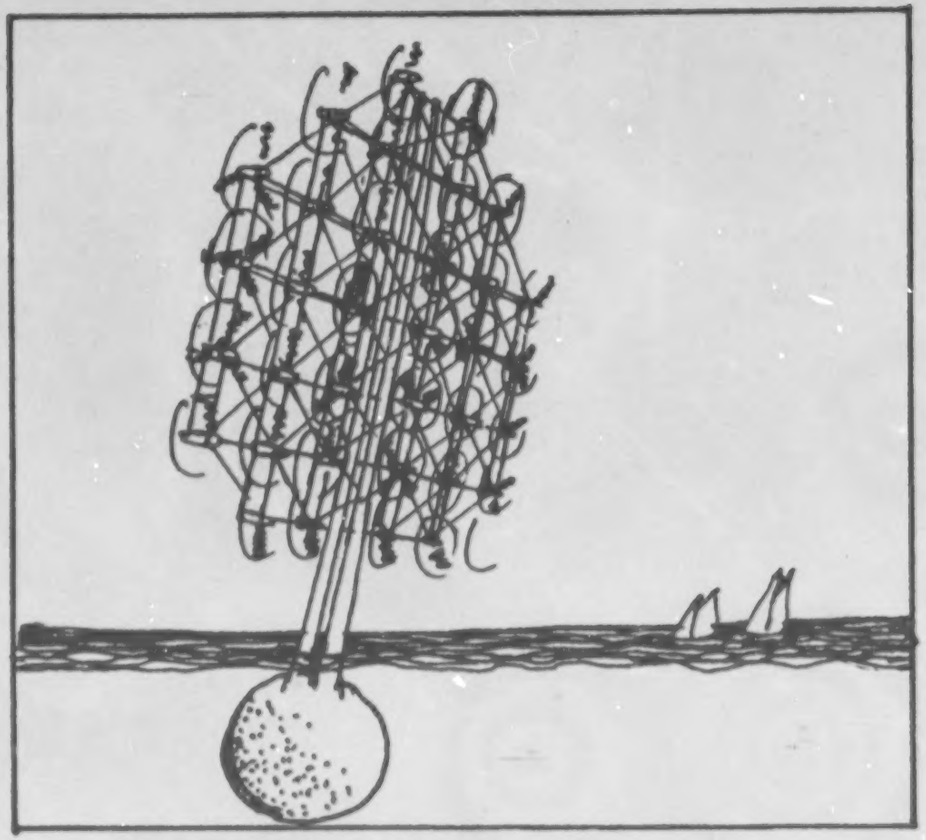
7. Vertical-Axis WECS — This type, often characterized by the Darrieus rotor patented in 1931, has the advantage of always being in the wind, rather than having to be oriented into changing winds like the horizontal-axis machines. It also offers the potential for locating mechanical equipment at ground level, greatly simplifying maintenance. This design does offer certain advantages over the horizontal-axis rotor, but it has a lower C_p (about 0.35), and is generally not self-starting.

8. Grandpa's Knob — The largest WECS ever built was installed at Grandpa's Knob, near Rutland, Vermont, in 1940. It was a private venture, led by the S. Morgan Smith Company of York, Pennsylvania. The WECS, rated at 1250 KW, or 1.25 megawatts, fed power into the lines of the Central Vermont Public Service Corporation for a period of 18 months. Following a generator main-bearing failure in February 1943, the system was shut down for a period of two years due to a wartime shortage of replacement bearings. The stresses developed in the blades over this two-year period of time were so great that, shortly after the machine was placed back in operation, it threw one of its 8-ton blades, thus ending what today would be termed a most successful experiment.

5.

9. ERDA/NASA Mod 0 — This design, erected at Sandusky, Ohio, reflects renewed government interest in large-scale systems. The machine, rated at 100 KW in an 18-mph wind, employs a 125-ft. diameter, two-bladed turbine in a downwind configuration. Initial test results have been poor, with turbine vibrations induced by both tower shadow and wind shear. Tower shadow is that turbulent effect created by the disturbance of the air stream as it passes through the tower on its way to the lower blade. Wind shear is the problem created when the wind blows at a lower windspeed on the lower blade than it does on the upper blade, which can be as much as 125 feet higher. While NASA attempts to solve these problems by streamlining the tower and reducing the turbine weight, contracts have been awarded for the development of 200 KW and 1500 KW WECS. Work has also begun on a turbine with a diameter of 300 feet.





10. Offshore Wind Power System — William Heronemus, professor of civil engineering at the University of Massachusetts, has proposed the construction and installation of several thousand large wind turbines off the Atlantic Coast. He has calculated that such a system could supply all of New England's electrical needs in the year 1990 at a reasonable cost.

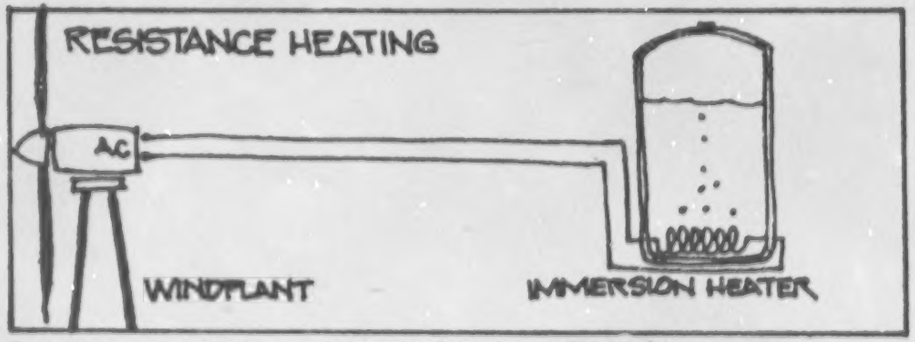
He has built a 10-meter diameter turbine and generator at the University of Massachusetts to serve as a test bed for his theories.

6.

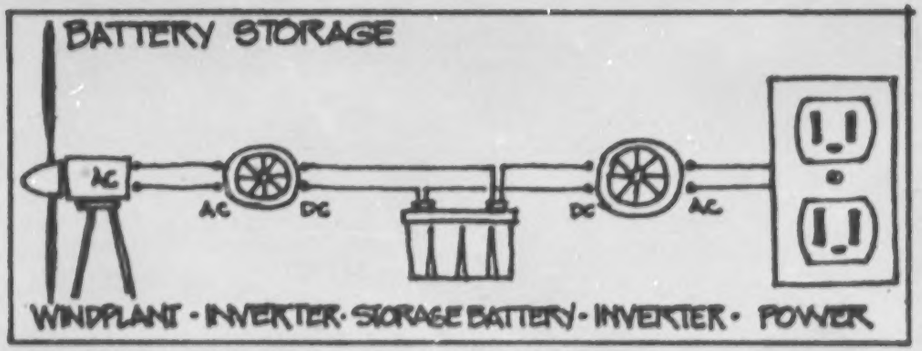
Utilization

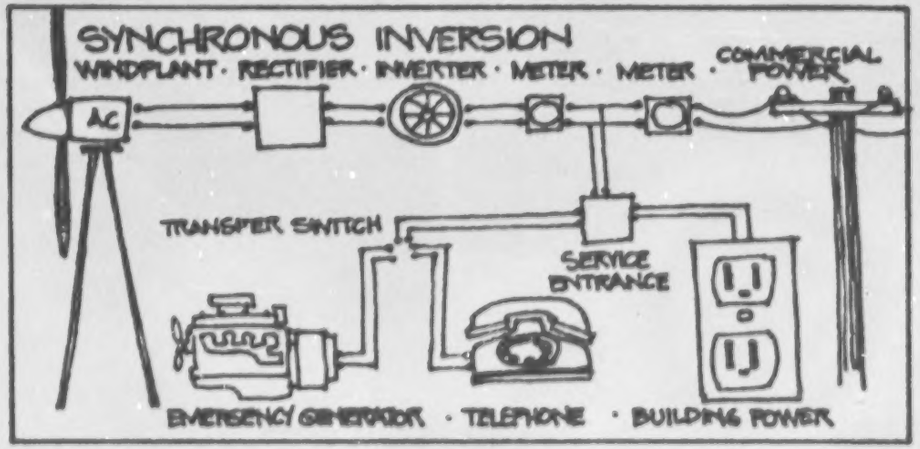
Given a properly-sized and durably designed WECS, effective conversion and storage systems must be added to complete the installation. The fundamental problem lies with the varying intensity of the wind versus the requirement for constant frequency AC power, as well as the demand for power when the wind may not be blowing. While present-day options are limited, current research holds much hope for technological advancement in this area. Some storage and conversion options are:

1. Resistance heating — The simplest and least expensive of currently available options, this interface can take the AC output from an alternator and, without regard to control of frequency or voltage, feed it into a resistance heating element like the immersion heater found in a hot-water heater or nichrome wire used in space heaters. The direct use of the WECS output for heat makes considerable sense in northern climates, since heat requirements increase when the wind blows. In this case, the more the wind blows, the more heat energy the user receives.



2. Battery storage — Although this is perhaps the most common WECS interface, battery storage is undesirable in terms of efficiency, expense, space and maintenance. As the diagram shows, DC power must be fed into the batteries, which, in the case of an alternator, requires conversion to AC power with consequent losses in efficiency. When power is drawn from the battery on demand, and, in most cases, converted back to AC power, further losses in efficiency result.

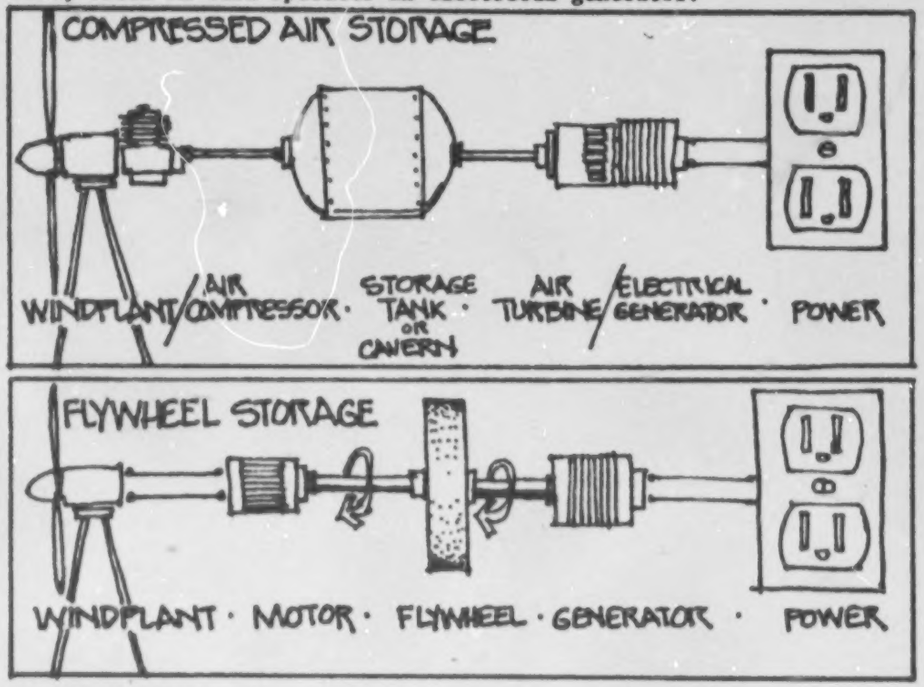



SYNCHRONOUS INVERSION
WINDPLANT · RECTIFIER · INVERTER · METER · METER · COMMERCIAL POWER
AC
TRANSFER SWITCH
SERVICE ENTRANCE
EMERGENCY GENERATOR · TELEPHONE · BUILDING POWER

3. Synchronous Inversion — A relatively recent innovation in the windpower field, synchronous inversion uses the output from a central generating plant to convert the varying output of a windplant to 60 Hz, 220 V, AC power. Since the WECS is tied directly into the utility grid, it can feed power to that grid when it is extracting power from the wind in excess of current demands. Conversely, if the wind is not blowing hard enough, the user can purchase power from the grid to meet the load demand. While thus buying and selling between the customer and the utility poses some new economic questions, there are at present many such systems in operation today.

4. Pumped Storage — The water-pumping windmill at the Maine Audubon Society is a small-scale example of a simple pumped storage system. When the wind blows, water is pumped to a high reservoir; it flows downward by gravity on occasions when the wind is not blowing. A larger-scale example would be a series of windmills employed at a large hydroelectric site to pump water, either mechanically or electrically, from an auxilliary reservoir below the dam back into the main reservoir behind the dam. As electricity is needed, this water is allowed by gravity to flow through a water turbine, which in turn spins an electrical generator. This in effect stores the energy extracted from the wind, allowing it to be used whether or not the wind is blowing.

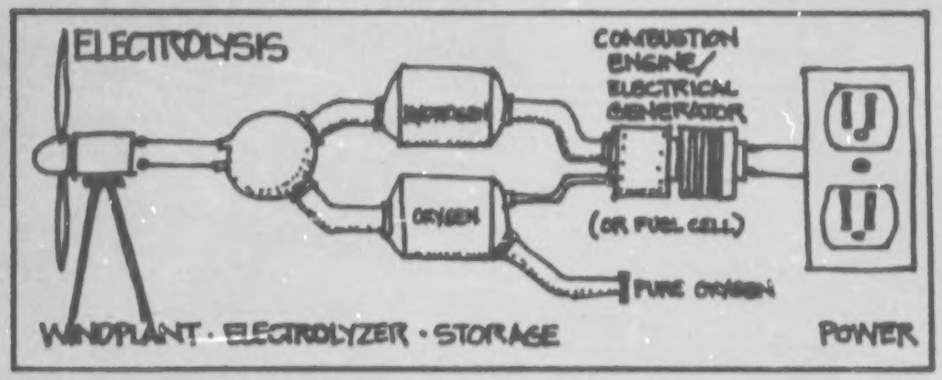
5. Compressed Air Storage — Similar in concept to pumped hydro storage, experiments are now going on in Eastern European countries to store compressed air in abandoned underground mine shafts. When the wind is blowing, the WECS supplies power to an air compressor, which feeds its output into an underground cavern. As electricity is needed, the compressed air is released from the cavern to turn an air turbine, which in turn operates an electrical generator.



6. Flywheel Storage — A flywheel can store more energy per mass weight than a battery can. The flywheel stores kinetic energy to be released as called for. With recent advances in light-weight, high-strength composition materials technology, and frictionless bearings, a flywheel could store 30 to 40 times as much energy per pound as a lead-acid battery could. The flywheel would be engaged to a motor/generator shaft to recover the stored energy.[4]

8

7. Electrolysis — The use of a WECS to supply electricity for the breaking down of water into its constituent elements of hydrogen and oxygen has begun to gain particular favor in offshore applications. The oxygen and hydrogen can then be stored for use when desired, or converted back to electricity by being passed through a hydrogen fuel cell.



Conclusion

There is little question among scientists that the technology exists today to extract significant amounts of energy from the wind. A massive commercialization program is required to convince American industry to undertake WECS production on a large scale, thus reducing costs to reasonable levels.

Footnotes

[1]National Science Foundation/National Aeronautics and Space Administration (NSF/NASA) Solar Energy Panel, Solar Energy as National Energy Resource, College Park, Maryland: University of Maryland (December, 1972), pp. 65-68.

[2]Clark, Wilson, Energy for Survival, New York: Anchor Books (1975), p. 564.

[3]Federal Energy Administration Project Independence Blueprint, Final Task Force Report: Solar Energy, Washington, U. S. Gov't. Printing Office, (1974), p. IV-1.

[4]Crowther, Richard, Sun/Earth, Denver: Hirshcfield Press (1976), p. 78.

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